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PREFACE

It is an objective of this series to make available to professional agronomists surveys or reviews of the progress in agronomic research and practice. The subjects selected for treatment this year are unrelated. The precedent of selecting for special consideration the problems and trends in land use and agricultural production in a geographical region with some degree of unity with respect to soils, climate, and practice has been continued. This year it is the Old Cotton Belt of the southern United States which has come under review. Because of economic pressures of various sorts, the agronomic pattern within this region is undergoing great change. Many adjustments have had to be made; others are still in progress.

Soil properties and soil–plant relationships lie at the core of many of the topics treated in this series. The chapters on zinc deficiency and phosphorus fixation fall in this category. Basic to such matters lie the recognition and identification of like soils. Pedology knows no national boundaries. There is a long tradition of close cooperation among workers in soil classification and genesis. Political boundaries have no meaning on soil maps. Once again there is presented an authoritative review of work in this field. Tavernier and Smith, in the chapter on Braunerde, attempt to clarify some of the nomenclatural confusion that can arise in a largely descriptive science.

Special reference ought to be made also to the paper by Kempthorne in which he points out the contributions made by the application of statistical methods to agronomy. Reading between the lines, however, one can also appreciate the substantial additions made to statistical theory by those who have been stimulated by the problem of analyzing data obtained in agronomic and genetic investigations.

A. G. NORMAN

Ann Arbor, Michigan
October, 1957

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THE CONCEPT OF BRAUNERDE (BROWN FOREST SOIL) IN EUROPE AND THE UNITED STATES

By R. Tavernier, *(State) University at Ghent, Ghent, Belgium*
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AGRICULTURAL TRENDS IN THE OLD COTTON BELT

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I. Introduction

The Old Cotton Belt, as defined for the purpose of this discussion, includes an area of about 300,000 square miles, lying across eight southeastern states in which cotton has traditionally dominated the economy (Fig. 1). It is recognized that the eight states of North Carolina, South Carolina, Georgia, Alabama, Tennessee, Mississippi, Arkansas, and Louisiana are the oldest cotton producers in the South, although some cotton was grown in eastern Texas as early as 1850. Also, owing to physical and economic characteristics shared by these eight states, it

appeared desirable to restrict the present discussion to this area. This is one of the oldest major agricultural areas of the country, and it has experienced many changes in soil-management and crop-production practices during its history.

Most of the Belt has been farmed for at least 150 years. The earliest settlements were made around 1700 along the Atlantic and the Gulf coasts. The inland part of the region was settled primarily by migration from the Atlantic Coast, and so the western part of the region was, in

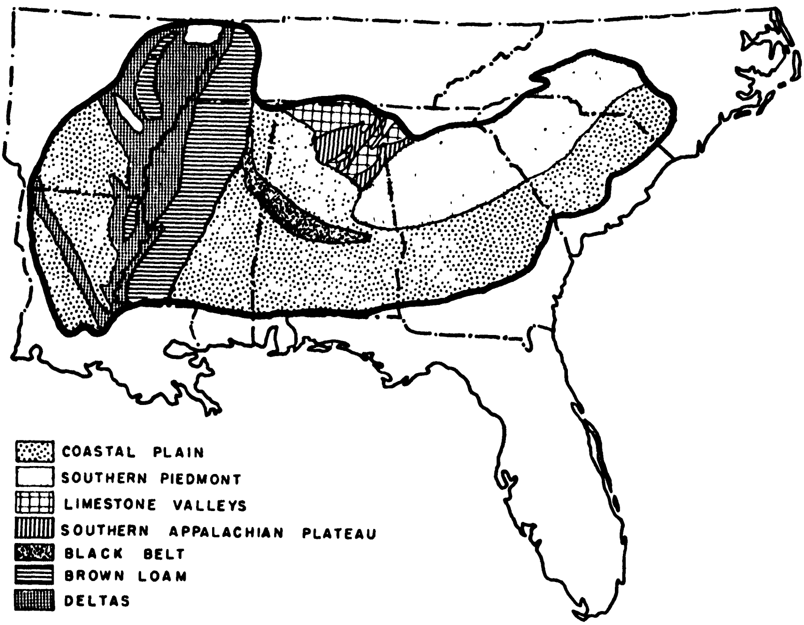

FIG. 1. Major physiographic regions of the Old Cotton Belt.

general, the last to be brought into cultivation. Most of the alluvial soils of the Mississippi flood plains, for example, have been cleared within the past 75 years.

The original settlers were of Anglo-Saxon extraction, and this influence is still strong in the social pattern of the region. With the exception of a few localities such as the Black Belt and parts of the Delta, relatively small family-operated farms have continued to be the rule, with cotton furnishing the mainstay of income.

II. Regional Characteristics

Soil-management practices must be modified and adapted to fit environmental conditions. It would be helpful, therefore, in understanding

the shifts that have been taking place in the agriculture of the region to have at hand information on such regional characteristics as climate, topography, soils, and water resources. These factors are discussed briefly in the following sections.

1. Climate

The chief characteristic of the climate is the long growing season that favors a wide variety of agricultural enterprises. The number of frost-free days varies from about 200 in the northern part of the Belt to as high as 260 in the southern part. The summers are hot and humid and the winters are mild. The temperature averages about 85° F. during the summer months and about 45° F. in the winter, with few periods of sufficiently low temperature to cause the ground to freeze.

The average annual rainfall ranges from 50 to 60 inches, with 50 inches being more representative of the entire area. More than half of the total precipitation occurs during the cool season of November to March. September and October are the driest months in the year, usually having less than half the average monthly rainfall. Rainfall during the spring and summer often comes as short, high-intensity thundershowers, whereas during the winter it comes usually in low-intensity rains over extended wet periods.

2. Physiography

Seven distinct physiographic regions are represented in the Old Cotton Belt. These regions are differentiated in geology, topography, native vegetation, and, as a result, in soils. The regions as shown in Fig. 1 are the Coastal Plain, Southern Piedmont, Southern Appalachian Plateau, Limestone Valleys, Black Belt, Brown Loam, and the Deltas. They will be briefly described in connection with a subsequent section on the soils of the area.

The topography of the Belt is extremely variable. Extensive areas of level to gently rolling land occur in the Deltas, Black Belt, and Limestone Valleys, and smaller areas are found in the southern and eastern reaches of the Coastal Plain. The slopes become generally steeper toward the northern and western edge of the Coastal Plain, terminating in the Clay Hills, Piedmont, and the Southern Appalachian Plateau. In the mountainous sections of the Belt, small areas of cultivated land are usually found in the valleys and on the ridge tops, with the slopes left in forest.

Elevation of the land surface varies from less than 100 feet in parts of the Deltas to more than 2000 feet on the ridges of the Southern Appalachian Plateau. In general, the elevation decreases from its high point in the north central part of the Belt toward the South and East.

With the exception of the Deltas and immediately adjoining areas the drainage pattern is made up of a network of rivers that rise in the northern part of the Belt and flow south and southeast together with many smaller streams that rise further south in the Coastal Plain.

3. *Soils*

The soils of the Old Cotton Belt, like those of the entire Southeast, were developed under climatic conditions that favored rapid weathering and a high degree of leaching. With the exception of the Black Belt, they were developed under forest vegetation, and although there was a wide variety of parent materials, this difference has been in a large measure overshadowed by the effects of climate and vegetation. The warm humid climate also prevents the accumulation of appreciable amounts of soil organic matter. Thus, the soils of this area are predominantly acid in reaction and low in organic matter and plant nutrients. These characteristics probably are responsible for the widely held misconception that the soils are unproductive. Actually, most of the soils are very responsive to good management, particularly to fertilization. In recent years it has become increasingly evident that yields can be attained that are comparable to those on the most fertile soils of the country.

Inasmuch as the soils of this area form the basic resource, a more detailed examination of their characteristics and management would be useful background information against which the agricultural trends can be presented.

The area that has been designated as the Old Cotton Belt of the Southeast includes seven physiographic regions, as outlined in Fig. 1. The soils of these regions fall within the Red and Yellow Podzolic Great Soil Group, except for the Black Belt and Deltas, which are classed by the U.S. Soil Survey (1954) as belonging to the Rendzina and Alluvial Major Soil Groups, respectively. In discussing the soils of the Belt under the physiographic region headings, the terminology most widely understood is used.

a. Coastal Plain. The Coastal Plain province accounts for about one-half of the total area of the Cotton Belt. The elevation lies between 100 and 700 feet above sea level. The soils were developed for the most part under pine forests, from unconsolidated marine-deposited sands and clays. They are, with few exceptions, sandy-textured in the surface horizon. The topography is undulating to rolling, and both surface and internal drainage are generally good. A comprehensive discussion of land use and development in this province is presented by Anderson (1956).

Typical upland soil series of this subregion are Norfolk, Ruston, Marlboro, Orangeburg, Red Bay, and Magnolia. They characteristically have sandy surface horizons varying in color from gray to reddish-brown and in thickness from 5 to 10 inches. Underneath is an 18- to 30-inch layer of yellow to red friable sandy clay B horizon, underlain by gray to red, mottled, unconsolidated sands and clays.

These soils not only have been subjected to a high degree of weathering and leaching during formation but were developed from parent materials that had experienced a previous cycle of weathering, leaching, erosion, and deposition. Consequently, they have a very low native supply of plant nutrients and are acid in reaction. Total potassium and phosphorus contents as low as 1000 and 500 p.p.m., respectively, are not uncommon in the plow layer (Davis, 1936).

The Sand Hills form a distinct subdivision within the Coastal Plain that should be mentioned, even though it has not been separately delineated in Fig. 1. The Sand Hills form a relatively narrow belt of deep sands lying along the fall line between the Coastal Plain and the Piedmont area extending from central North Carolina to the vicinity of Columbus, Georgia. The predominate soils are Kershaw and Lakeland sands and loamy sands. Similar soils occur in spots throughout the Coastal Plain, and wherever they occur they present the same management problems of extremely low plant-nutrient supply and low water-holding capacity.

b. Southern Piedmont. This subregion forms about 13 per cent of the Belt and occurs in four of the eight states that constitute the Belt. The soils in the Piedmont were derived from granites, gneisses, and schists and range in texture of the surface horizon from sandy loams to clay loams. Internal drainage is generally good in the upland members. Cecil is the most extensive soil type. Other soils of this subregion are Madison, Lloyd, Appling, Durham, and Georgeville.

The Cecil, which is the most prominent and one of the redder members of this group, typically has a gray sandy loam to red clay loam surface horizon, depending upon the degree of erosion. This layer is underlain at 4 to 8 inches by a red, stiff, but brittle, clay subsoil. A lighter colored, more friable clay usually occurs at 30 to 40 inches.

The topography of the area is rolling to hilly, and this together with the lack of stable soil structure has resulted in widespread and severe erosion. A good example of this is the extensive occurrence of Cecil clay loam, which originally had a sandy surface horizon long since lost, exposing the red clay or clay loam B horizon. These eroded soils often present a considerable problem because of their poor physical condition and low water infiltration rate, which is usually less than ½ inch per hour.

The present fertility level of the soils of the Piedmont is relatively high compared with some of the coarser textured soils of the Southeast. This is particularly true with reference to potassium (Welch and Nelson, 1951). Although the native phosphorus content of these soils was very low, an accumulation from fertilizer applications over the years has resulted in a considerably higher level of available and total phosphorus. Organic matter and nitrogen are very low in these soils, as is true for other soils of the Southeast.

c. Black Belt. The soils of the Black Belt or Black Prairie, as this area is sometimes called, belong to the Rendzina Great Soil Group, and the region derived its name from the dark brown to black color of the soils. They were developed from chalk and very heavy marine clay deposits under grass vegetation on undulating topography. The area occurs only in Alabama and Mississippi in the Southeast and constitutes less than 10 per cent of the arable land in each of these two states.

About one-third of the soils of the Black Belt are calcareous, the chief series in this category being Sumter and Houston. In the rest of the area, gray to red acid-clay soils occur, including the Vaiden, Eutaw, and Oktibbeha as the most extensive series. They are sticky when wet and form large cracks when dry. The Sumter, which is generally considered to be an eroded phase of Houston, is an extensive series, occurring typically on the slopes. A survey of Perry County, Alabama, in 1902 shows that Houston clay was the predominant type in the Black Belt; whereas by 1930 the Sumter series had largely replaced it (Scarseth, 1932).

Although these soils occur in a region underlain by limestone, the soils are often extremely acid. They were also very low in available phosphorus in the virgin state. Their native potassium content was relatively higher than that of the adjacent Coastal Plain soils.

d. Limestone Valleys. This subregion falls chiefly in the Tennessee and Coosa river valleys of Alabama and constitutes only about 6 per cent of the Belt. The soils belong to the Red and Yellow Podzolic and Reddish Brown Podzol Great Soil Groups. They were derived primarily from limestone under hardwood forests, and as a result have a considerably higher inherent fertility level than most of the soils of the region. They vary in color from red to reddish-brown and in texture from silt loams to clay loams.

The soil series mapped include Dewey, Decatur, Cumberland, Fullerton, and Clarksville. The topography is undulating to rolling, and the internal drainage is generally good. Decatur is typical of the better soils of the area.

e. Southern Appalachian Plateau. This physiographic province occurs in the northeast corner of Alabama and the northwest corner of Georgia. It consists of a series of relatively smooth-topped ridges, lying in a northeast-southwest direction, and forms a very small but important segment of the Belt.

The agriculturally important soils belong to the Red and Yellow Podzolic Great Soil Group and are in many respects quite similar in properties and use and management requirements to the upland soils of the Coastal Plain. They are derived from interbedded sandstones and shales under hardwood forests. The topography is rolling, and internal drainage is good. The soils are predominately very fine sandy loams and silt loams. They are characteristically acid in reaction, are low in organic matter and plant nutrients, and have a relatively high silt content. Those derived from shales are somewhat finer textured, shallower, and, in general, less productive than are those developed from sandstone.

Hartsells is the most important soil series. It has a grayish-brown, very fine sandy loam A horizon extending to a depth of 6 to 9 inches, underlain by a yellowish-brown friable sandy clay B horizon. The C horizon of weathered sandstone usually occurs at 2½ to 3½ feet.

The Enders is generally considered to be the most important series of those developed from shale. It usually has a silt loam surface underlain by a clay loam B horizon, and occurs on steeper topography than does the Hartsells, making it particularly susceptible to erosion.

Most of the soils of this subregion have unusually high silt contents and, as a result, form oriented particle crusts upon drying after a rain. These crusts are sometimes very troublesome in preventing seedling emergence and in reducing infiltration of water.

f. Brown Loam. This physiographic province, which constitutes about 10 per cent of the old cotton-producing area of the Southeast, forms a belt lying east of the Mississippi flood plain and extending from northwestern Tennessee southward across Mississippi to the tidewater region of the Gulf Coast. Several smaller areas occur west of the Mississippi River, also. A mantle of wind-deposited silt lies over the marine sands and clays of the Coastal Plain throughout this subregion. The thickness of the loess varies markedly from east to west, being thickest along the Mississippi River bluffs. It thins out and finally disappears some 30 to 50 miles to the east. The topography generally varies from undulating to rolling.

The principal upland soils are Memphis, Loring, Grenada, Callaway, and Henry, listed in order from good to poor drainage. The texture of their surface horizons is predominately silt loam, although frequently erosion has removed this layer, exposing the original B horizon.

In such cases, the surface is somewhat finer textured. The profiles are well developed, and in all the members except the Memphis a distinct fragipan occurs at depths varying from 12 to 30 inches.

Nitrogen, phosphorus, potassium, and calcium are generally deficient in the soils of this province. In this respect they differ but little in degree from those of the Coastal Plain.

g. Deltas. The flood plains of the Mississippi, Yazoo, White, Arkansas, and Red rivers comprise this subregion, which includes about 17 per cent of the Old Cotton Belt.

The soils are, in general, the most fertile of any in the entire Southeast. They are derived entirely from sediments deposited by rivers and are extremely variable as to texture and degree of internal drainage. Their common characteristics are topography, which is gently undulating to level, immaturity, and relatively high fertility level, particularly with respect to phosphorus, potassium, and other bases. Prominent soil series, listed in order of increasing fineness from sandy loam to heavy clay, are Bosket, Dundee, Dublos, Mhoon, Commerce, Sharkey, and Alligator. These soils exhibit only faint horizon differentiation owing to the relatively short period of time the parent materials have been in place. A recent excellent discussion of these soils is available (Fowlkes *et al.*, 1956) for those who wish to study them in more detail.

4. Water Resources

The southeastern United States is a region of many rivers and smaller streams fed by a relatively high rainfall. The water resources, both above and underground, are here, but systematic development of these resources is still in its infancy. One of the most critical factors relating to water development and use for urban, industrial, agricultural, or recreational purposes is the lack of up-to-date regulatory legislation. Throughout the South present statutes are still based on the Riparian Rights doctrine (Scheele, 1952), although its obsolescence in the face of increasing competition for this resource has been repeatedly demonstrated. This problem has been widely recognized, and nearly every state in the South is currently studying its water-rights laws with a view to revision.

Water is an all important factor in the current trends of both agriculture and industry and will have a marked influence on the future growth and development of this area. For this reason, and in view of the limited data available for many of the states, the water resources of Alabama will be briefly discussed as being typical of the Southeast.

Swingle (1955) has calculated that there are 9764 miles of major creeks and larger streams, with a total surface area of 111,581 acres, within Alabama. In addition to the streams, large impoundments

add 241,820 acres, and the 11,852 farm ponds in the state increase the water area by another 50,176 acres. This, together with 354,503 acres of brackish water in the extreme south, makes the total area of usable water 758,080 acres, or an average of 1 acre of water for every 43 acres of land. Omitting brackish water, the ratio becomes 1 acre of fresh water for every 80 acres of land.

Alabama can also be considered typical of the Belt with respect to the runoff and water conservation problem, since it has essentially the same ranges in topography, soils, and management practices that are found in the rest of the region. It has been calculated that of the 54 inches of rain that fall on the average within Alabama, about 16 inches are lost through surface runoff. It is part of this fraction of the water supply that the farm-pond construction program is aimed at conserving for useful purposes.

Pollution of streams in the Southeast is a problem of tremendous importance. Large quantities of industrial wastes and laxity on the part of towns and villages in proper treatment of sewage are creating a serious situation in many sections. There is increasing concern about this problem, and corrective steps are being taken in many areas.

Underground water resources vary tremendously among the different physiographic areas of the region. In the Piedmont and Appalachian Plateau areas, the yields of wells are generally very low, ranging from 2 to 50 gallons per minute, and the cost of drilling is high, making underground water a relatively unimportant source except for family or village use. In the Limestone Valleys, on the other hand, large underground streams flow through solution channels, and when these are tapped the yield is generally very high. In the Coastal Plain, which forms a major part of the region, subsurface water is quite variable in quantity and depth. Yields of wells vary from 40 to 500 gallons per minute at depths of 200 to 1400 feet.

In the Delta there is generally an abundant supply of underground water at relatively shallow depths. Many wells have been sunk in this area during the past few years for irrigation of cotton, and flows of better than 1000 gallons per minute are not uncommon. The depth to water in the Delta varies from 10 to 30 feet, but well depths generally run somewhat above 100 feet to reach the strata having sufficient high capacity for irrigation supply.

The amounts and depth of underground water in the Brown Loam area are much the same as in the Coastal Plains, as would be expected. The average capacity of over 3000 wells in the Brown Loam area of Mississippi (Mississippi Water Resources Policy Commission, 1955) has been reported to be 175 gallons per minute. Very few exceed 500 gallons per minute flow.

III. Problems Influencing Agricultural Trends

As competition in agriculture becomes keener and more intensive production practices have to be adopted in the Belt, myriad problems are encountered that must be solved either directly or indirectly by modification of the farm operation to fit the circumstances. Several of the more important of these factors are considered briefly here.

1. *Soil Fertility*

Low inherent soil fertility is the first limiting factor in crop production in the Belt. Since the soils are acid in reaction and low in organic matter and plant nutrients, a progressive liming and fertilization program is essential to any type of farming. Unlike many other parts of the country the agriculture of this area is absolutely dependent upon commercial fertilizers. Even though their native fertility is low, the soils of the Belt are very responsive to fertilization, and yields of adapted crops comparable to those in the best farming areas of the country are often made in favorable years. At the same time the use of high rates of fertilizer represents an operating cost that can strongly influence the over-all plan for the farm operation.

Phosphorus was usually the most critically limiting element in the virgin soils of this area, except in the Deltas. Now, however, after the use of phosphate fertilizers for many years, most of the soils have a considerably higher level of available phosphorus (Gholston, 1956; Wilson, 1956; Welch and Nelson, 1951). Of course, past fertilization practices varied widely from farm to farm, with the result that the level of soil phosphorus now varies in a random fashion and is related to few if any observable soil characteristics. This simply means that any rational fertilization program, at least with respect to phosphorus, must be based on soil test information.

Potassium was relatively higher in the virgin soils of the Belt than was phosphorus, but since it does not accumulate appreciably under the soil and climatic conditions of the region it has become much more deficient with time. Here, again, wide variations exist as a result of past cropping and fertilization treatment. For example, cotton on fields previously planted to peanuts for several years without adequate additions of potassium, will often be a complete failure owing to extremely low levels of potassium in the soil. This is in spite of the fact that the peanuts probably produced satisfactory yields.

Although fertilization with potassium is required for maximum production of any crop on practically all soils of the Belt, it is particularly important in the case of forage crops such as alfalfa and the clovers.

Nitrogen has for many years been the most generally limiting element for the growth of nonlegume crops in the Belt. Corn yields without nitrogen rarely run above 20 bushels per acre on upland soils, regardless of other factors. With adequate nitrogen and other good management, yields of above 100 bushels are quite common (Krantz and Chandler, 1954; Jordan, 1951). Similarly, yields above 500 pounds of seed cotton can rarely be made without nitrogen, as compared with yields of 2000 pounds and above with proper fertilization. Large amounts of nitrogen are required by most crops, and since nitrogen does not accumulate in the soil to any extent and since the efficiency of recovery by crops is poor, it will continue to be one of the most important single problems of crop production in the Southeast.

Liming has generally been considered a necessary step for forage crop production, but there has been a strong tendency to neglect it as an important part of the general farm management plan. As a result the area now finds itself in a serious position with respect to soil acidity, and the increasing use of acid-forming nitrogen fertilizers is aggravating it. Recent soil test laboratory summaries have shown that some 75 per cent of the soils are too acid for best growth of legumes, and 25 to 50 per cent need liming for satisfactory growth of an acid-tolerant crop such as cotton. Estimates are that up to 15 million tons of limestone per state would be required to bring its arable soils up to the recommended level of pH. Annual maintenance requirements would range around 1 or 2 million tons per state as compared with the present average use of about one-tenth of that amount.

2. *Soil Erosion*

Control of soil and water loss is a major problem affecting land use and soil management throughout the Old Cotton Belt and one that has greatly influenced shifting management patterns in the area. The topography of much of the region is hilly, and this fact, together with the frequent high-intensity spring and summer rains and the inherent erosivity of many of the soils, explains the importance of runoff and erosion control in any stable system of agriculture. This is particularly true of the Brown Loam and Piedmont regions as well as of the clay hill section of the Coastal Plain.

The early agriculture of the Belt was based entirely on a row-crop system of farming centered on cotton, and little attention was given to the problem of erosion control. When fields became gullied or marred by "gall spots" owing to removal of the surface soil and exposure of unproductive subsoil they were abandoned. There were many instances of abandonment of entire farms, and the results are evident to the casual observer traveling through the Piedmont or

Brown Loam areas today. These areas usually grew up in pine, broom sedge, and other native grasses that have for the most part halted further depredation. In more recent years, with increasing concentration of the paper industry in the Southeast and with expanding livestock production, there has been considerable interest in the reclamation of abandoned areas for pulpwood, forage crops, and even row crops under improved management. The economic feasibility of such reclamation is strikingly shown in a recent study by Ulrich (1953), who analyzed the capital costs of getting land into agricultural production in the semiarid West and the humid Southeast. He concluded that after allowing for differences in inherent productivity of soils in the different areas 6.25 equivalent acres could be brought into production in the Piedmont region for the cost of each acre in the Columbia Basin area of the Northwest. Since there are several million acres of reclaimable land not now in production in the Belt, this would form an important reserve of relatively easily restored production.

The erosion hazard in parts of the Brown Loam region is even more critical than in the Piedmont. The high sand and silt content of the soils and the widespread occurrence of a strong genetic pan combined with the hilly topography have often resulted in extreme gullying to the extent that some areas are useless for any kind of agriculture.

Even though the problem is widely recognized and a great deal of effort is being directed toward getting proper land-use and soil-management practices adopted, the erosion hazard will continue to exist as one of the predominant factors influencing agricultural trends in the more susceptible parts of the Belt.

3. *Moisture Relationships*

The relatively high annual rainfall of the Belt might lead one to expect that lack of moisture would not be a problem in crop production. In order to understand the problem as it exists, however, several factors must be considered. In the first place much less than half of the total rain occurs during the six-month period April to September during which crop growth occurs. Then too, much of the rain that is received during this period comes too rapidly to be taken in by the soil, and relatively high runoff losses often occur. In addition, the high summer temperatures result in large evapotranspiration losses of moisture. Values exceeding 0.3 inch per day are not uncommon. As a result of these factors and the relatively low available water-holding capacities of many of the soils of the Belt, there is no doubt but that moisture is limiting for crop growth during some periods of most years.

Increasing competition, acreage controls, labor shortages, and other factors are more and more demanding higher per acre yields, espe-

cially of crops requiring relatively high cash outlay for production. This situation, together with the dramatic effects of occasional drought years, has brought supplemental irrigation to the forefront as a means of increasing average crop yields and providing insurance against crop failure in years of extreme drought. Tremendous advances have been made in this direction in the Mississippi Delta, for example, where the level topography, large fields, and abundant water supply are combined to make conditions for irrigation exceptionally favorable. The phenomenal increase in irrigation in this area is illustrated by Fig. 2, which

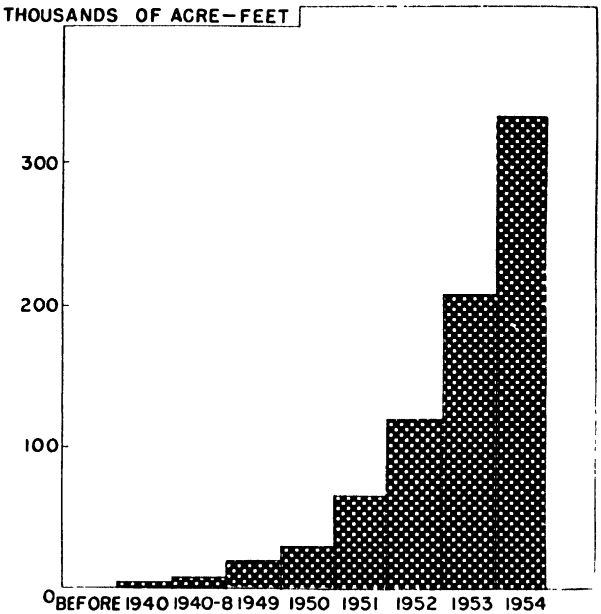

FIG. 2. Estimated pumpage from wells for irrigation in the Mississippi Delta by years (Mississippi Water Resources Policy Commission, 1955).

shows the amounts of water calculated to have been pumped from wells for irrigation from 1949 through 1954. Prior to 1950 little water was used for irrigation. Since that time, however, each succeeding year has seen a 70 to 100 per cent increase over the preceding year. Of course, these figures do not give an estimate of total irrigated area because a large amount of water is pumped from the numerous streams and bayous. Although a breakdown of the use of water by crops is not available, it is a matter of record that rice has risen from a position of insignificance to that of a relatively important crop in this part of the Belt during the period covered in Fig. 2. In 1950, for example, only 7000 acres of rice were grown in Mississippi, all of it in the Delta. By 1954

there were 84,000 acres of rice, a twelvefold increase in five years. However, the increase in use of irrigation in the Delta cannot be attributed primarily to increased rice acreage. Supplemental water is more and more being used on cotton to insure maximum yields on a part of the acreage of many plantations, and for pasture and forage production during the dry, late summer and fall seasons. Both research and practical experience are showing that the practice is economically sound.

There has also been a rapid rise in the use of irrigation in other parts of the Belt, particularly in the Coastal Plain and Limestone Valleys regions, for both row and forage crops. This trend is illustrated in Table I. Data on new irrigation systems by years for Alabama are con-

TABLE I
New Irrigation Systems Installed in Alabama and Acreage Covered, 1949–1955[1]

Year	Number of new irrigation systems	Acreage in these irrigation systems	Acres/system
1949	17	269	16
1950	45	1,108	25
1951	77	3,342	43
1952	174	7,813	45
1953	100	4,955	50
1954	211	12,529	59
1955	405	17,366	43

[1] Personal communication from Lawrence Ennis, Extension Specialist, Soils Engineering, Alabama Polytechnic Institute.

sidered to be typical for the bulk of the Old Cotton Belt. Relatively few of these irrigation systems were installed in the Piedmont or the Black Belt. Most of them were in the Coastal Plains. With the one exception of 1953, there was an approximate 100 per cent increase in the number of new systems installed and an even higher rate of increase in acreage irrigated each year during the period 1949 to 1955. Table II shows that cotton accounted for about one-third of the total new acreage in 1955, with corn, pasture, and truck crops following in that order.

Several factors must be considered in attempting to evaluate the effect of irrigation on over-all production levels in the Belt. Certainly crop yields on individual farms will be drastically increased, and levels will be raised appreciably within areas especially suited to the use of irrigation, such as in the Delta and in parts of the Coastal Plains. However, the problems of inadequate water supply, rolling topography, financing, and the high level of over-all management that is absolutely necessary to make supplemental irrigation a paying proposition, will put definite limits on the influence it can have in the Belt as a whole. It seems

reasonable to expect that cotton production levels in the Belt may be affected more than those of most other agricultural crops. This is true because of the response of cotton under intensive management to supplemental irrigation and its high cash return per acre at known yield potentials.

Tobacco is a crop of localized importance in the Old Cotton Belt. Most of the area devoted to its production in the Southeast lies in the lower reaches of the Coastal Plain, where cotton has never been of primary importance. However, areas lying within the Belt in North Carolina, South Carolina, and Georgia that have fairly extensive acreages of tobacco (Anderson, 1956; Wilson and van Bavel, 1954) have

TABLE II
New Irrigation Systems and Acreages Used for Various Crops in Alabama. 1955[1]

Crop	No. of new systems	Acreage
Cotton	41	5,920
Corn	148	4,408
Pasture	63	3,267
Truck crops	113	2,143
Other	40	1,628
Total	405	17,366

[1] Personal communication from Lawrence Ennis, Extension Specialist, Soils Engineering, Alabama Polyechnic Institute.

shown that tobacco responds markedly to supplemental irrigation in this area. This, together with acreage control and the high per acre value of the crop, means that irrigation can be expected to be used for tobacco production as extensively as water supplies and other limitations will permit.

In spite of the rapidly increasing importance of supplemental irrigation in this area it seems that the development of improved and practical management practices that will increase the effectiveness with which the natural precipitation is utilized offers more real promise of general improvement in crop production levels across the Belt than does irrigation. There is a special need for management practices that will increase the amount of water entering the soil profile during the crop growth season.

At the other end of the soil moisture range there are many areas of poor drainage in the Old Cotton Belt. Drainage is an especially important problem on the finer textured soils of the Deltas, in the Black Belt, and in many of the valleys of the Piedmont. In some instances drainage has been indirectly responsible for major shifts in land use. An excel-

lent example of this is furnished by the Black Belt, which, until the advent of the boll weevil around 1920, had the highest concentration of cotton farms in the Southeast. The soils on which cotton was grown at that time were very fine-textured and had retarded internal drainage. Thus, they could not be planted as early as the better drained upland soils. The boll weevil is particularly destructive of late crops. As a result, cotton production on prairie soils of the Black Belt rapidly declined, and farmers on these soils turned to crops better adapted to the soils. Today livestock production predominates in the area.

4. *Biological Factors*

Biological factors have played an important role in soil management in the Old Cotton Belt. Certain changes in land use, shifts from one-crop to more diversified farming, and development of livestock in this area have been affected by plant diseases, the boll weevil, and other biological factors. These factors have accounted for serious losses in farm income in many instances. Specific biological factors which limit yields are not always apparent. Likewise, the detrimental effects of biological factors are difficult to measure.

In the case of cotton, certain biological factor data are available. By 1904, the boll weevil was reported in western Louisiana. In 17 years from this date, it was reported in North Carolina, having moved east and north from the point of entry completely across the Southern United States.

Actual boll weevil damage varies from year to year. Mild winters and excessive rainfall during the summer months are conducive to boll weevil activity. Boll weevil damage may run as high as 50 per cent or more of the crop (Agelasto *et al.*, 1921).

In Alabama, from 1909 to 1950, insects and diseases were responsible, on the average, for a 17.5 per cent reduction in cotton yields, or slightly more than half the reduction due to all causes. Of the 17.5 per cent reduction from "full" or "normal" yields due to the biological factors, 13.9 per cent was from the boll weevil, 2.0 per cent from plant diseases, and 1.6 per cent from other insects. Of the 15.6 per cent reduction resulting from nonbiological causes, 5.4 per cent was due to excessive moisture, 5.3 per cent to deficient moisture, 3.4 per cent to other climatic conditions, and 1.5 per cent to all other causes. In terms of yields per acre, therefore, plant diseases and insects alone were responsible for an average annual reduction of 43 pounds of lint cotton per acre from 1909 to 1950 (Lanham *et al.*, 1953).

For the eight states included in the Old Cotton Belt, the boll weevil accounted for an average reduction of 15.4 per cent in yield from 1920 to 1929. Including the destructiveness of other insects with that of the

boll weevil, the reduction from full yield was 18.4 per cent in this period. These data are shown in Table III. Considerable variation in reduction from full yield of cotton existed over the area. For example, from 1920 to 1929 the average reduction in yield due to boll weevil damage varied from 23.1 per cent in Georgia to 4.9 per cent in Tennessee. Deficient moisture was of second most importance in the reduction of cotton yields. In this connection it should be recognized, however, that

TABLE III
Average Percentage Reduction from Full Yield of Cotton per Acre by 10-Year Periods, Old Cotton Belt, 1909–1949[1]

Cause of reduction in yield	Average percentage reduction from full yield			
	1909–19	1920–29	1930–39	1940–49
Boll weevil	7.8	15.4	9.2	11.0
Other insects	2.3	3.0	1.6	1.3
Plant diseases	2.0	1.3	2.0	1.2
Deficient moisture	6.8	7.0	8.9	4.8
Excessive moisture	6.5	6.6	3.0	5.2
Other climatic	5.6	3.0	4.4	3.6

[1] Source: Averages were calculated from data reported in *U.S. Dept. Agr. Statistical Bull.* **99**, 68–78. "Statistics on Cotton and Related Data," June, 1951.

yield reductions were calculated from state average yields. Thus, conditions that would cause a given yield reduction due to deficient moisture at the 300 pound level of lint would have a considerably more serious effect where management practices are intensified to produce, say, 1000 pounds of lint.

IV. Major Trends

A number of changes in agriculture have taken place in the Old Cotton Belt during the past quarter century. These embrace changes in broad uses of land, importance of crops, livestock, livestock products, machinery and equipment, facilities, and farm practices, and farmers themselves. A number of changes have been accelerated in recent years.

These changes, in a large measure, have arisen from farmers' adjustments to physical, economic, social, institutional, and biological factors. Reorganization of farms, often to increase size or to take advantage of machinery and machine efficiency, has taken place. The relative profitableness of different crop and livestock enterprises has influenced changes that have taken place. This relative profitableness of enterprises has been affected by advances in science and in the arts. In addition, government programs, institutional factors, and forces which reflect

changes in demand for agricultural products have had their effect on agricultural trends in the area.

What are some of the major trends and changes in land use and soil management, machines, facilities, and farm people in the Old Cotton Belt? Some of these are discussed in the following section.

1. Changes in Cotton

Although cotton is still the major cash income crop in the Old Cotton Belt, its importance has declined. Numerous economic and institutional forces have brought about a decrease in cotton acreage. The effects of the boll weevil were discussed above. In addition, the depression of the 1930's, government programs, and World War II with labor and material shortages have played important parts in the decline.

TABLE IV

Average Yields of Cotton (Pounds of Lint) per Acre, Old Cotton Belt, 1910–1955[1]

Period	Average yield per acre (lb.)	Standard deviation (lb.)	Coefficient of variation (%)
1910–19	208	33	16
1920–29	191	39	20
1930–39	246	50	20
1940–49	314	58	18
1950–55	344	75	22

[1] Source of yield data: *U.S. Dept. Agr. Statistical Bull.* **99**, 35–49. "Statistics on Cotton and Related Data," June 1951; *Statistical Bull.* **99**, 46–59 (revised), Feb. 1957. Standard deviations and coefficients of variation were calculated from yield data for each of the eight states.

In 1930, 74 per cent of the farms in the Old Cotton Belt compared to 54 per cent in 1950 reported cotton harvested.[1] Ninety per cent of all farmers in Alabama and Mississippi reported cotton harvested in 1930.

The cotton acreage harvested as a proportion of total cropland harvested declined from 43 per cent in 1930 to 29 per cent in 1950 as an average for the eight southern states included in the Old Cotton Belt.

Total cotton production did not decline as much as acreage. In 1930 the eight states produced 8.8 million bales. In 1950, they produced 6.8 million bales. Thus, production decreased only 23 per cent, whereas acreage declined 40 per cent. Obviously yields per acre have improved.

Average yields of cotton by 10-year periods and for the 5-year period 1950 to 1955 show considerable improvement (Table IV). A

[1] Many of the data in this and following sections are reported for census years. In many cases the information is applicable to the year preceding the census. The 1955 census data were not available for all eight states included in the Old Cotton Belt at the time this manuscript was prepared.

number of things contributed to this marked improvement in yields. In 1930, farmers in the area applied an average of 262 pounds of commercial fertilizer per acre to cotton. In 1940, they applied 276, in 1950, 380, and in 1953, 403 pounds of commercial fertilizer per acre. The strong trend in recent years toward higher analysis fertilizers would magnify the increase in plant nutrient use. Better varieties, improved

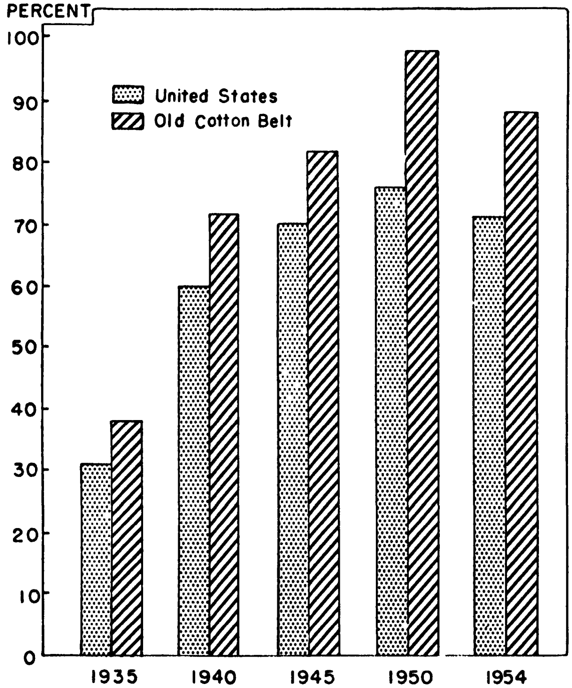

FIG. 3. Percentage of cotton ginned 1 inch or longer in staple length, United States and Old Cotton Belt, 1935–1954 (Cotton Quality Statistics, United States, U.S. Dept. Agr., 1935–1954).

cultural practices, and numerous other things also contributed to yield improvement.

Two measures of variability, standard deviation and coefficient of variation, were calculated for each group of average yields per acre. These data show that variation in cotton yields was approximately 75 per cent greater in 1940 to 1949 than in 1910 to 1919, whereas yields were about 50 per cent greater. However, relative to average yields, variation in yields has changed little during the past 45 years.

Improvement also was made in the staple length of cotton produced in the Old Cotton Belt (Fig. 3). In 1935, somewhat more than

one-third of the cotton ginned in the area was 1 inch or longer in staple length; in subsequent years there was a rapid increase until at present better than 90 per cent is 1 inch or longer. Relative to cotton produced in other areas, the Old Cotton Belt has also progressed in improvement of staple length since 1935.

2. *Land Use*

Approximately 60 per cent of the land in the states included in the Old Cotton Belt was in farms in 1950 (Table V). This represented an increase of 14 per cent over 1930. In the United States, 61 per cent of the total land area was in farms in 1950. In total, there were 147,155,241 acres in farms in the Old Cotton Belt in 1950. About one-eighth of the total land in farms in the United States is included in the Old Cotton Belt.

Cropland harvested was reported as 43,360,083 acres in the area in 1950; thus, almost 30 per cent of the land in farms was cropland harvested. The same relationship of cropland harvested to total area of land in farms existed for the United States in 1950.

From 1930 to 1950, harvested cropland acreage in the Old Cotton Belt decreased from 48.8 to 43.4 million acres. The decrease in cotton acreage more than accounted for the total decline in harvested cropland. The area occupied by corn and several other crops also declined. Thus, certain other agricultural uses of land increased. Since numbers of farms in the area declined during the 1930 to 1950 period, harvested cropland per farm changed very little.

The major increases in land use that occurred in the Old Cotton Belt 1930 to 1950 were for land pastured, for the production of hay, soybeans, oats, peanuts, and for woodland. Land pastured and farm woodland each increased by approximately 16 million acres during the 20-year period. Soybeans harvested for beans became an important crop. Peanuts increased to occupy 1⅓ million acres as the result of expansion during World War II; since then, the acreage has declined. Oats harvested for grain also increased from about 300,000 acres in 1930 to 1⅓ million in 1950. Although the acreage of several harvested crops increased, the decrease in acreage of cotton, corn, and certain other harvested crops exceeded the increase. It seems logical that the net decrease in harvested cropland was accounted for by the increase in land pastured, woodland, and other miscellaneous uses.

Space does not permit a discussion of changes in yields, total production, and farming practices in connection with each of the major crops. Much of agriculture as it exists today in the Old Cotton Belt bears little resemblance to that of a quarter century ago.

TABLE V
Changes in Acreage and Proportion of Land Used for Various Purposes in the Old Cotton Belt, 1930–1950*

Item	Unit	Census of: 1930	Census of: 1950	Per cent change
Total land area	Acres	240,142,080	240,540,800	+0.2
Land in farms	Acres	128,825,316	147,155,241	+14.2
Proportion of land in farms	%	53.6	61.2	—
Total woodland	Acres	46,827,911	63,247,279	+35.1
Proportion woodland of land in farms	%	36.3	43.0	—
Woodland pastured	Acres	15,010,558	22,146,814	+47.5
Proportion of total woodland pastured	%	32.1	35.0	—
Land in lots, roads, waste, etc.	Acres	8,610,894	6,300,126	−26.8
Cropland idle[1]	Acres	9,712,140	10,302,131	+6.1
Cropland harvested	Acres	48,751,029	43,360,083	−11.1
Proportion cropland harvested of land in farms	%	37.8	29.1	—
Cotton	Acres	21,032,991	12,595,405	−40.1
Proportion cotton acreage of cropland harvested	%	43.1	29.0	—
Corn	Acres	18,328,251	14,822,107	−19.1
Proportion corn acreage of cropland harvested	%	37.6	34.2	—
Peanuts threshed or combined[3]	Acres	733,948[2]	1,348,000	+83.7
Oats threshed or combined	Acres	295,052	1,323,860	+348.7
Wheat threshed or combined[4]	Acres	751,109	860,348	+14.5
Tobacco	Acres	1,109,037	906,798	−18.2
Soybeans for beans[3]	Acres	66,006[2]	991,688	+1,402.4
Sorghum for all purposes except syrup	Acres	174,706	193,138	+10.6
Sweet potatoes (home use or sale)	Acres	456,156	286,642	−37.2[5]
Irish potatoes (home use or sale)	Acres	220,415	129,535	−41.2[5]
Other vegetables (harvested for sale)	Acres	406,890	483,023	+18.7
Land from which hay was cut	Acres	2,546,718	5,482,246	+115.3
Land pastured	Acres	29,933,900	46,092,436	+54.0

[1] Land not harvested and not pastured.
[2] 1920 figure.
[3] Solid equivalent in area.
[4] Acreage for 7 states—not available for Louisiana.
[5] A part of the decline in acreage of sweet and Irish potatoes was due to not including acres for farms with less than 15 bushels harvested in 1949.
* Source: "1930 Census of Agriculture," U.S. Dept. Comm., Bureau of Census, Vol. II, Part 2; 1950 Census of Agriculture, Vol. I, Parts 16, 17, and 20–24.

The importance of corn, however, cannot be overlooked. In 1950, it occupied a greater acreage than cotton. Improvement in average yields of corn came about after the 1930's (Table VI).

The acreage of corn planted with hybrid seed has shown a steady increase during the past ten years. In 1945, less than 10 per cent of the acreage of corn for the states included in the Old Cotton Belt was planted with hybrid seed compared to 64 per cent in 1956. Four of the eight states reported more than 70 per cent of their corn acreage planted with hybrid seed in 1956.[2] This, along with changes in spacing, heavier fertilization, and improved cultural practices, made possible the increased yield per acre.

TABLE VI

Average Yield of Corn per Acre in Old Cotton Belt, 1910–1955[1]

Period	Bushels
1910–19	18.8
1920–29	16.6
1930–39	14.8
1940–49	19.1
1950–55	21.8

[1] Source: Calculated from data in "Crop Production," Crop Reporting Board, U.S. Dept. Agr., Washington, D.C., 1910–1955.

The increased use of commercial fertilizer for cotton, corn, and other crop and pasture enterprises as indicated by actual amounts and by the trend toward higher analysis materials constitutes a major change in soil management during the past quarter century. Fertilizer consumption per farm doubled from 1930 to 1950 in the Old Cotton Belt (Fig. 4). For the United States it more than doubled from 1930 to 1950. In interpreting these results it should be borne in mind that higher analysis materials are used in general in other parts of the United States than the Old Cotton Belt.

3. *Shifts to Livestock*

Changes in numbers and production of livestock and poultry constituted major trends during the past quarter century in the Old Cotton Belt. The number of cattle and calves on farms increased from 6 million to almost 12 million head in the eight states of the area during the 25 years from 1930 to 1955 (Fig. 5). The number of milk cows showed

[2] "Hybrid Corn," Crop Reporting Board, U.S. Dept. Agr., Washington, D.C., 1945–1956.

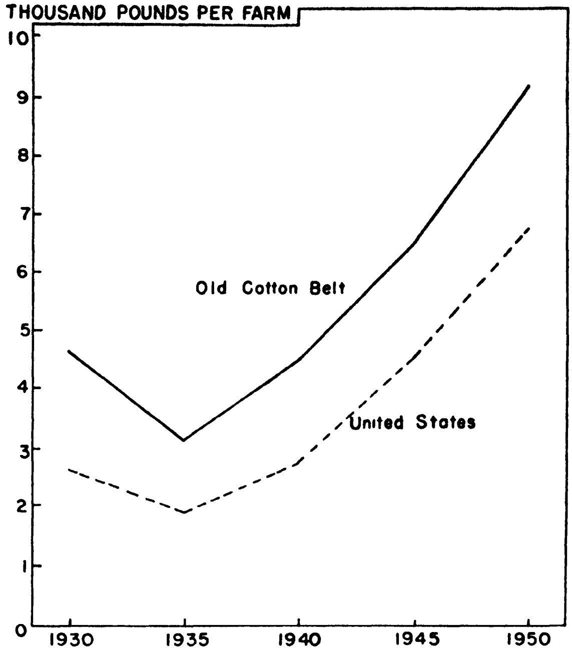

FIG. 4. Average consumption of commercial fertilizer per farm, Old Cotton Belt and United States, 1930–1950 (Agricultural Statistics, U.S. Dept. Agr. and U.S. Census of Agr., 1930–1950).

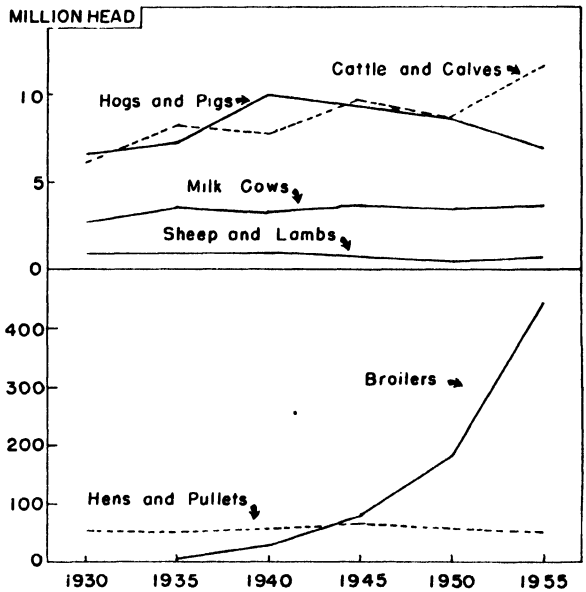

FIG. 5. Changes in numbers of livestock, hens, and pullets on farms and broilers produced, Old Cotton Belt, 1930–1955 (Livestock and Poultry on Farms and Ranches, January 1, U.S. Dept. Agr., 1930–1955).

relatively less change during this period. The number of hogs and pigs on farms has registered an increase of about 4 per cent since 1930. The number of stock sheep and lambs on farms declined from 1930 to 1950; however, the 1955 figure was 170,000 more than that in 1950. The number of hens and pullets on farms has fluctuated rather widely. From a low of 47.2 million in 1935, the number of hens and pullets on farms in the area climbed to 64.1 million in 1945 and since has declined.

Tremendous expansion has taken place in broiler production in the Old Cotton Belt. Small farms, long on labor relative to capital assets and often with relatively poor soil resources, have found broiler production a favorable enterprise. Also, various financing arrangements with feed companies, banks, and other organizations and institutions have made possible the rapid expansion of broiler production.

TABLE VII
Number of Broilers Produced in the Old Cotton Belt as a Percentage of the U.S. Total[1]

Year	Per cent
1935	12.6
1940	16.3
1945	21.7
1950	30.7
1955	41.2

[1] Source: "Farm Production Disposition and Income Chickens and Eggs," U.S. Dept. Agr., Washington, D.C., 1935–1955.

In 1955, the eight states of the Old Cotton Belt produced 444.4 million broilers. In 1935, broiler production in the area was only 5.4 million birds. The area now produces approximately 40 per cent of all broilers produced in the United States (see Table VII).

The increase in importance of livestock and livestock products in the Old Cotton Belt is reflected in changes which have come about in the composition of cash farm receipts. Livestock now accounts for almost 33 cents out of each dollar of cash farm receipts compared to 18 cents during 1925 to 1929 (Table VIII). Increases in the proportion of cash farm receipts from cattle and calves, hogs, and chickens (including broilers) have been somewhat greater than the increase in cash farm receipts from dairy products.

Income from cotton and cottonseed accounted for more than 50 per cent of total cash farm receipts in the Old Cotton Belt in 1925 to 1929. It steadily declined to 33.1 per cent of the total during 1950 to 1954.

TABLE VIII
Proportion of Total Cash Farm Receipts from Various Sources by 5-Year Periods, Old Cotton Belt, 1925–1929 to 1950–1954[1]

Source of cash receipts	1925–29	1930–34	1935–39	1940–44	1945–49	1950–54
	%	%	%	%	%	%
Cotton and cottonseed	56.1	46.4	42.2	37.3	33.6	33.1
Peanuts	1.4	1.8	2.3	4.0	3.5	2.4
Corn	1.2	1.1	1.5	1.6	2.0	1.4
Soybeans	0.2	0.2	0.3	0.5	0.7	1.4
Truck crops	2.5	2.6	2.4	2.4	2.3	1.9
Forest products	2.1	2.4	2.2	1.6	1.6	2.5
Other	18.4	24.7	26.3	25.5	26.8	25.1
Total crops	81.9	79.2	77.2	72.9	70.5	67.8
Cattle and calves	3.3	3.7	5.4	5.7	7.7	7.8
Dairy products	5.3	7.9	6.8	6.9	6.7	7.3
Hogs	3.4	3.1	5.0	6.5	6.6	6.5
Chickens (incl. broilers)	1.9	2.1	1.9	3.4	4.0	5.8
Eggs	3.6	3.2	3.0	3.9	3.5	3.9
Other	0.6	0.8	0.7	0.7	1.0	0.9
Total livestock and livestock products	18.1	20.8	22.8	27.1	29.5	32.2

[1] Source: "The Farm Income Situation," U.S. Dept. Agr., Washington, D.C.

Thus, cotton remains the largest single source of cash farm receipts, but it has descended the income ladder by many rungs.

4. *Fewer and Larger Farms*

The trends in numbers and average size of farms in the Old Cotton Belt were similar to those taking place in other areas of the United States. The number of farms in the area decreased from 1.9 million in 1930 to 1.6 million in 1950 (Fig. 6). As an average, farms increased in size from 67 acres in 1930 to 92 acres in 1950. Thus, numbers declined 16 per cent while the average size increased 37 per cent.

This increase in size along with more machinery, equipment, livestock, and other production items meant added capital investment per farm. It also made possible a larger volume of farm business per farm.

Changes in capital investment, with particular reference to the increased size of farms, are reflected, at least in part, by changes in the reported average values of land and buildings per acre in the Old Cotton Belt. In 1930, the average value of farm land in buildings in the area studied was $36 per acre. In 1955, it was $81—an increase of 125

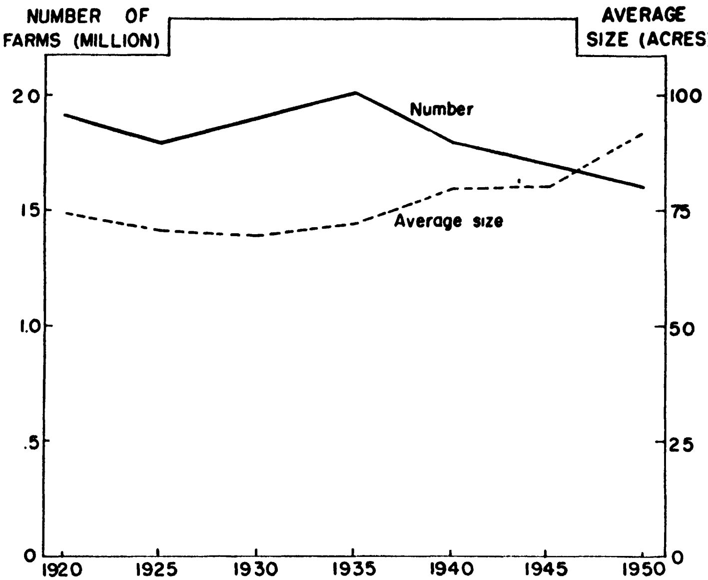

FIG. 6. Number and average size of farms, Old Cotton Belt, 1920–1950 (U.S. Census of Agriculture, 1920–1950).

per cent. During the same period, farm land and building values increased 61 per cent from $49 to $79 per acre in the United States.[3]

5. *More Machines and Facilities*

Much of the area of the Old Cotton Belt does not lend itself to maximum use of tractors and tractor equipment. However, mechanization has made considerable progress in the area. About 4 per cent of all farmers reported a tractor in 1940. In 1950, almost 20 per cent of all farmers in the Old Cotton Belt reported one or more tractors. The total number of tractors increased from 78,946 in 1940 to 418,033 in 1950. In 1940 the number of tractors per 100 acres of harvested cropland was 0.16; but in 1950 it was 0.96.

While tractors on farms were increasing, the number of mules and horses was declining. Farmers in the Old Cotton Belt reported 3,153,000 mules and/or horses in 1930. By 1950, the number declined to 1,646,000 —a 48 per cent drop. Almost 80 per cent of all farms reported mules and/or horses in 1930 compared to 64 per cent in 1950.

In addition to tractors, numerous other machines such as corn pickers, combines, hay balers, fertilizer spreaders, field forage har-

[3] 1930, 1940, 1950 and 1954 Census of Agriculture, U.S. Dept. Comm., Bureau of Census, Washington, D.C.

vesters, dusters, milking machines. and many others have increased in numbers.

The availability of electrical power has been another important factor influencing certain trends in the agriculture of the area. Farm work has been made easier and farm life less different from that of urban areas as the result of electricity on almost 70 per cent of all farms in the area in 1950. In 1940 only 16 per cent of all farms in the Old Cotton Belt had electricity. Also, some progress has been made in the proportion of farms with telephones, although only 10 per cent of all farms reported a telephone in 1950. Hard-surfaced roads have been important contributors to the changes which have taken place. The proportion of all farms located on hard-surfaced roads increased from about 4 per cent in 1930 to 23 per cent in 1950.[4]

6. Fewer Farm People

Total farm population in the Old Cotton Belt declined during the past quarter century, an era of change. For every 100 persons on farms in 1930, there were only 77 persons in 1950. During the period, total population increased from 19,046,247 to 22,748,936 a 19.4 per cent increase or almost 1 per cent per year.[5]

It is interesting to note that although the rural farm proportion of total population decreased from 51 to 33 per cent, the rural nonfarm proportion increased from 1930 to 1950. In 1950, 27 per cent of the total population of the area was classified as rural nonfarm; in 1930 it was 21 per cent. Thus, in 1950 the Old Cotton Belt was still predominately rural (60 per cent of total population).

The change in rural farm population meant more land per person on farms. As an average, for the area there were 13 acres of farm land per farm person in 1930 compared to 20 acres in 1950.

Tenure of farm operators also has not gone without change. As a whole, the proportion of tenancy declined from 62 per cent in 1930 to 41 per cent in 1950. In 1950 there was approximately one-half as many cash tenants in the area as in 1930. Likewise, share tenants and croppers declined in numbers. Many croppers and tenants who left the farms were colored. Nonwhite farm operators constituted 37 per cent in 1930 compared to 29 per cent of all farm operators in the Old Cotton Belt in 1950.

Changes in agriculture and the rapid advance of industrialization in the Old Cotton Belt fostered increased emphasis on work off the

[4] 1930, 1940, 1950 and 1954 Census of Agriculture, U.S. Dept. Comm., Bureau of Census, Washington, D.C.

[5] 1930 and 1950 Census of Population, U.S. Dept. Comm., Bureau of the Census, Washington, D.C.

farm. Less than 10 per cent of all farm operators reported 100 days or more of work off their farm in 1930. But in 1950, 21.6 per cent reported work of 100 days or more off the farm.

With the decline in number of farms and farm people, changes in farm production, and increases in farm size, farm income per farm and per person increased from 1930 to 1950. This is true even after adjustments are made for changes in the price level. Average cash farm receipts per farm from crops, livestock, and livestock products were \$553 in 1930, \$564 in 1940, and \$2282 in 1950. Using the index of prices received by farmers (1910—14 = 100) for all farm commodities for the United States[6] as a deflator, the average cash farm receipts per farm were \$442, \$564, and \$884, respectively, for the years indicated above.

Average cash farm receipts per farm person in the Old Cotton Belt increased from \$108 in 1930 to \$496 in 1950—a 359 per cent increase. From 1930 to 1950 in the United States, per capita, income payments increased from \$596 to \$1439 or 141 per cent.[7] Thus, a marked increase in income per person occurred in the Old Cotton Belt; however, in 1950 cash farm receipts per person were approximately one-third those of the United States average. Cash farm receipts did not include any value on farm-produced products used in the home or rental value of the home.

V. Summary

Far-reaching changes have occurred in the agriculture of the Old Cotton Belt during the past quarter century. Cotton acreage and income have become less important in relation to other enterprises. The increase in acreage of pasture and in acreage and production of feed grains and forage crops has been highly significant. Yields and quality of certain crops have improved. Livestock numbers and production as well as poultry enterprises have greatly expanded. The role of forests and forestry products has been recognized as an important one.

Farms have increased in size and declined in numbers. Tractors, other machines, electrical power, improved roads, numerous facilities and improvements have become prevalent in the area. While total population and industrialization moved ahead, farm population declined. Tenant farm operators decreased in numbers and as a proportion of all farm operators. As a result of these and other changes farm income per farm and per person on farms increased substantially over that which prevailed a quarter century earlier.

[6] "Agricultural Statistics, 1954," p. 473. U.S. Dept. Agr., Washington, D.C.

[7] "Survey of Current Business," August, 1952, p. 11. U.S. Dept. Comm., Washington, D.C.

The future of agriculture in the Old Cotton Belt is not without problems. Nevertheless, the future appears bright if certain trends and changes discussed above continue. These include an increase in land, livestock, machinery, and fertilizer per farm and per farm worker and the continued opportunity for those not fully employed on farms or for those who have small farms to find adequate nonfarm employment. In general, the changes discussed mean more complex types of farming. Thus, managerial skills must also progress along with advancements in the sciences and their application on farms in the Old Cotton Belt.

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ZINC DEFICIENCY AND ITS CONTROL

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I. Introduction

Zinc deficiencies of plants are dramatic because of combinations of chlorosis, rosetting, dieback, and depressed or abnormal vegetative

growth. A wide variety of plants are affected, but deficiencies are most common in fruit crops. Sweet cherries, peaches, apricots, apples, pears, walnuts, citrus, tung, and grapes are highly susceptible. Corn, *Zea mays* L., is perhaps the most widely affected of annual crops. Viets *et al.* (1954a) list beans, soybeans, corn, hops, lima beans, flax, and castor beans as very sensitive to zinc deficiency. Potatoes, tomatoes, onions, alfalfa, grain sorghum, Sudan grass, sugar beets, and red clover were noted as mildly sensitive. Peppermint, oats, wheat, barley, rye, peas, asparagus, mustard, carrots, safflower, and grasses were described as

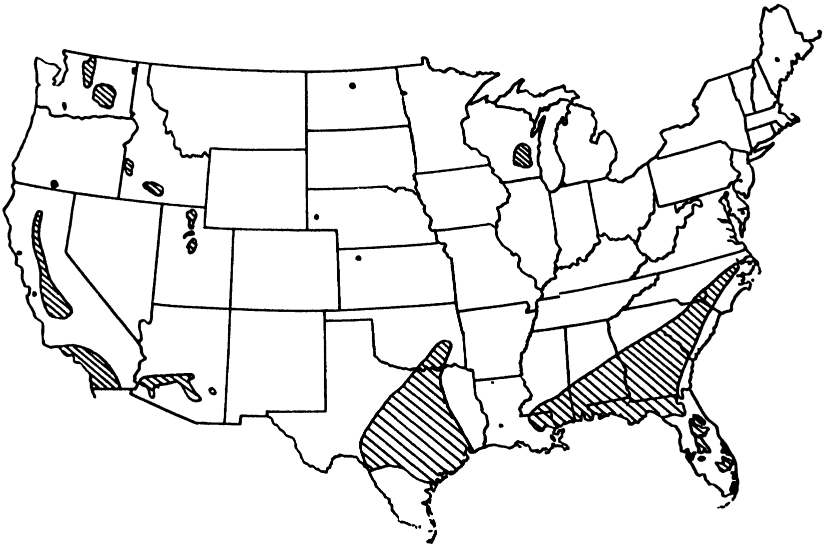


FIG. 1. Areas of the United States reported as deficient in zinc. (Adapted from map prepared by K. C. Beeson, U.S.D.A. Soil and Plant Nutrition Laboratory, Ithaca, New York, 1956.)

insensitive to the deficiency. Zinc deficiency is known by various names including little leaf, rosette, dieback, bronzing, yellows, and white bud.

Zinc deficiency has been observed most extensively in the United States and Australia, but it occurs under field conditions in at least 20 different countries (Chilean Nitrate Educational Bureau, 1948, 1951, 1953, and 1955).

Wann and Thorne (1950) found zinc deficiencies reported by plant scientists in each of the 11 western states. Most recently Beeson (1957) has made a survey of nutrient deficiencies of crops throughout the United States. The areas where zinc deficiencies were reported are shown in Fig. 1. In California (Chandler, 1937) zinc deficiencies occur over an area more than 400 miles long and are considered an important,

economic, plant nutrition problem. Recently deficiencies have been encountered in a number of field and vegetable crops (Lingle and Holmberg, 1956) in addition to the extensive occurrence in fruit trees. Finch and Kinnison (1933) state that many pecan orchards were abandoned in certain valleys of Arizona because of rosette. Thorne and Wann (1950) found zinc deficiencies in 7 per cent of the fruit orchards in Utah. The pronounced deficiencies of zinc and copper in South Australia (Riceman, 1948), Victoria (Newman, 1956), and West Australia (Dunne and Elliott, 1950) have made Australia a center of research on these elements.

Zinc deficiencies occur on a variety of soils. Affected soils are usually of pH 6.0 or higher. Often they are sandy, although deficiencies have been found on fine-textured soils and on mucks and peats. Treatments with lime and phosphate fertilizers have been reported to induce zinc deficiencies in crops under some conditions. Old corral and barnyard sites often show zinc deficiencies.

II. Early History

Since zinc deficiency of plants is highly dramatic it would seem that it would have been identified long ago. But the rapid onset of the disease and the marked deterioration of affected plants were taken as evidence that the cause was not nutritional. Full confirmation of zinc as an essential element and the extensive recognition of zinc deficiencies under field conditions have come during the past 30 years. Earlier evidence of the need for zinc by plants was delayed by difficulties of freeing nutrient solutions and containers from traces of zinc.

As early as 1863 and 1869 Raulin presented evidence that zinc is needed for the growth of certain fungi in culture media. Javillier (1914) confirmed the need for zinc by *Aspergillus niger* and gave evidence that failure of others to get responses to zinc probably resulted from zinc impurities in the culture media. He (Javillier, 1912) also reported increased growth of wheat, oats, corn, lupines, and peas from soil treatments of 5.5 to 55 pounds of zinc sulfate per acre.

P. Maize, in a series of nutrient culture experiments, reported in 1914, 1915, and 1919, furnished the first convincing evidence that zinc is essential for higher plants. Its essential nature was not generally accepted, though, until Sommer and Lipman (1926) and Sommer (1928) reported studies similar to those of Maize showing that zinc is required by barley, sunflowers, buckwheat, beans, and vetch. These studies were soon followed by widespread reports of successful control of zinc deficiencies in the field through treatment with zinc. Beginning in 1927 workers in Florida (Allison *et al.*, 1927; Barnette *et al.*, 1936)

reported benefits to corn, peanuts, peas, millet, and other annuals from treatment with zinc sulfate. Also Alben *et al.* (1932) obtained responses in tung trees to zinc, and Chandler *et al.* (1932) secured benefits from treating various fruit trees.

III. Plant Symptoms of Zinc Deficiency

1. *Visual*

Lack of zinc results in distinctive plant symptoms associated with a retarding of normal growth and a lack of chlorophyll. In deciduous fruit trees the leaves are smaller than normal. They develop a yellow mottling between the veins. In early stages the chlorotic leaf pattern is seen as small isolated areas between the lateral veins. These gradually coalesce until continuous bands extend from near the middle to the outer edge, where they unite to form a continuous chlorotic leaf margin. Leaves are typically largest at the base of the tree and become smallest near the top. Terminal buds fail to elongate, with the result that a tuft of small leaves is produced forming a "rosette" at the end of twigs. As the deficiency becomes more severe, branches may die back; this is particularly marked in sweet cherry. In many instances the trees are not uniformly affected by the deficiency, so that flat-sided or lopsided trees are produced. The fruit may also be affected. Zinc-deficient Elberta peach trees, for example, bear a large proportion of small flat fruit. Hale peach trees, on the other hand, tend toward small elongated fruit (Amer. Soc. Agron., 1949; Stiles, 1946; Thorne and Wann, 1950).

Zinc deficiency is extensive in citrus and is commonly termed mottle leaf. The leaf pattern is marked by dark green veinal areas and lighter green interveinal tissues. Terminal twig growth is shortened, particularly on the south side of trees, and dieback is common. Oranges on deficient trees in California are small with thick skins. The pulp is woody, dry, and tasteless.

Zinc deficiencies in corn were noted early in Florida by Barnette *et al.* (1936). Initial symptoms are a light interveinal chlorosis of older leaves, which rapidly progresses to form a broad bleached stripe—six or more veins in width running from the base to the tip of the leaves. Severe stunting of the plants occurs and pollination is poor. Milo has similar symptoms.

Viets *et al.* (1954a) have recorded zinc deficiency symptoms in 26 different crops growing in the Columbia Basin area. The plants made poor growth; interveinal leaf chlorosis and necrosis of lower leaves were common. Reddish or brownish spots often occurred in the older leaves (Lingle and Holmberg, 1956). Seed production was often strikingly reduced.

2. *Cytology*

The cytology of leaves from zinc-deficient plants has been studied by Reed and his co-workers. One of the most marked characteristics is abnormal cell structure. The palisade cells of mottled citrus leaves (Reed and Dufrenoy, 1935) are broader than normal and divide transversely. Chloroplasts are few and full of oil droplets. Starch grains are usually absent. After treatment with zinc sulfate, starch grains appear, and oil and fat disappear. An abnormal shape of palisade cells and an almost complete absence of chloroplasts and starch were also observed in such other zinc-deficient plants as corn, tomato, buckwheat, and mustard (Reed, 1938). The plastids were often shrunken, and this was associated with agglutination of the plastids in the polar regions. Calcium oxalate crystals were often found in leaves and buds, indicating a disturbed carbon metabolism (Reed, 1941).

Of particular interest in Reed's studies is the accumulation of phenolic materials and tannins in leaves of many zinc-deficient plants. In some plants, such as apricots, the accumulation of phenolic materials was related to the intensity of zinc deficiency symptoms (Reed, 1938). Leaves of deficient corn and mustard were, however, free of such substances.

Reed and Dufrenoy (1942) stated that vacuolar sap normally contains both oxidizable phenol materials and polyphenol oxidase. They suggested that under normal conditions hydrogen donators such as ascorbic acid or cysteine protect the phenols. They postulated that when zinc deficiency disturbs the system the cell materials coalesce and form vacuolar aggregates with high polyphenol oxidase activity at the surface.

Carlton (1955) observed that zinc deficiency resulted in a cessation of meristematic activity in root tips and cambium of tomato. Roots of minus-zinc plants contained small tumors, similar to those formed on roots exposed to low concentrations of certain growth-regulating substances. The tumors developed a short distance behind the growing tips.

IV. Zinc Nutrition of Plants

1. *Absorption*

Zinc is readily absorbed from dilute solutions. Brown and Wilson (1952) obtained marked responses in cotton growth from the addition of 0.001 p.p.m. of zinc to purified solution cultures. Only 0.1 p.p.m. of zinc was needed in solution for normal growth of cotton and of pine seedlings (Wilson, 1953). This capacity of plants to secure needed

amounts of zinc from such low concentrations probably accounts for the lack of differences in zinc uptake from various materials.

Zinc is probably assimilated principally as the divalent ion, Zn^{++}, with the possibility of some assimilation in such monovalent forms as $(ZnCl)^+$. It is doubtful, however, that the pH of living roots would enable assimilation of measurable amounts of zincate ions which may occur under alkaline conditions.

Epstein and Stout (1951) adsorbed various proportions of radiozinc (Zn^{65}) on bentonite and measured uptake by tomato plants in relation to other adsorbed ions. With the quantity of zinc per culture held constant (12.8 gammas) the uptake of zinc increased in linear relation to the proportion of zinc adsorbed on the clay up to a level of about 0.1 per cent of the cation exchange capacity. When the zinc adsorbed on the bentonite was held constant at 0.1 per cent of the cation exchange capacity, the zinc content of tomato roots and tops was almost linearly related to the total zinc supplied to the roots. Maximum zinc content of the tomato tops occurred with the degree of calcium saturation of the clay between 50 and 75 per cent (between pH 5.0 and pH 5.6). Zinc in solution and the zinc content of roots decreased continually as the proportion of exchangeable calcium was increased.

Elgabaly *et al.* (1943) found that zinc uptake by excised barley roots followed closely the trends for potassium absorption. The roots obtained more zinc from zinc-bentonite than from zinc-kaolinite under comparable levels of clay saturation.

Zinc uptake by plants does not appear to be greatly influenced by moderate amounts of other ions or compounds except as they influence the amount of zinc in solution. Jurinak (1956) found a linear relation between zinc uptake by corn seedlings and the concentration of zinc in solution in the presence of calcite and dolomite.

Shaw *et al.* (1954) failed to find any appreciable difference in the amount or rate of zinc uptake by corn or citrus seedlings from soil treatments with various zinc materials labeled with radiozinc. The treatments included zinc sulfate, zinc carbonate, zinc applied as plant material, and zinc accumulated in the soil during the previous five years. In all cases the percentage utilization of the added zinc was low. In similar tests, Speer *et al.* (1952) found that crimson clover and rye grass readily assimilated zinc from calcareous Houston clay soil treated with zinc nitrate, zinc ammonium hydroxide, and sodium zincate.

2. *Translocation within Plants*

The translocation of zinc within plants may be influenced markedly by other ions or compounds. Biddulph (1953) reported that zinc was precipitated along the veins of plants grown in solutions high in

phosphate. Under high iron nutrition, zinc precipitation in conducting tissue was reduced, apparently because the concentration of soluble phosphate was reduced by precipitation with iron. Under conditions of low phosphate, zinc was distributed rather uniformly through leaves and was not markedly concentrated along the veins. Zinc, like iron and calcium, was not retranslocated from older leaves to younger leaves as the plants grow. Biddulph demonstrated translocation of Zn^{65} as well as Fe^{55} from leaves under conditions of low phosphate nutrition.

A related example of zinc fixation in plant tissues as a result of nutrition has been reported by Ozanne (1955a). Subterranean clover plants growing on soil low in zinc showed increased severity of zinc deficiency symptoms when the nitrogen supply was increased, regardless of the nitrogen source used. Under conditions of low zinc supply, the zinc concentration in roots was found to be correlated with the percentage protein nitrogen. The zinc content of plant tops decreased with nitrogen application. The fixation was interpreted as resulting from formation of immobile zinc-protein complexes bringing about zinc retention in the roots under conditions of high nitrogen and low zinc. The data of Bergh (1950) support this concept in that 77 per cent of the zinc retained in roots of pea plants was in the insoluble residue, whereas 60 to 85 per cent of the zinc in the top parts was soluble in cold water.

The results of Ozanne help account for the reports of Haas (1936), Chapman *et al.* (1937), Camp (1945), and Reuther and Smith (1950), wherein liberal applications of nitrogen fertilizers were reported to produce or increase zinc deficiency symptoms.

Ozanne (1955b) has also found that light conditions may influence zinc absorption and translocation. Subterranean clover plants took up more zinc under long-day conditions than under short-day conditions, but they also retained a larger amount of the absorbed zinc in the roots. The increased retention of zinc in the roots was attributed largely to increased root weights in relation to leaves. Under the same zinc supply, maximum deficiency symptoms occurred at about the same light intensity as that needed for maximum photosynthetic activity. An increase in high intensity above this resulted in decreased symptoms and more growth. It appeared that leaves growing under high light intensity were able to utilize zinc present in them more efficiently than leaves growing under medium light intensity. These results in Australia differ from the report of Hoagland (1944) that in California zinc deficiency symptoms are most apparent under summer conditions of high light intensity.

The data of Biddulph and Ozanne indicate that the distribution of zinc within a plant might be markedly influenced by the environment

in which the plant is grown. Conditions which alter zinc deficiency symptoms of plants have been shown, therefore, to act in three ways: first, by directly influencing the concentration of zinc in the soil solution; second, by altering the absorption of zinc by plants; and third, by directly or indirectly altering the retention of zinc within roots or other conductive tissues.

In view of reports that phosphate, iron, and nitrogen nutrition and light intensity influence the retention of zinc within plant tissues, it would be expected that data on zinc movement from one part of plants to other parts would be variable. Some data substantiating this are cited.

Wood and Sibly (1950) studied the redistribution of zinc in oat plants and concluded that no zinc was translocated from leaves to other organs, but that inflorescence zinc came from the roots and from the medium. Williams and Moore (1952) studied the distribution of zinc, copper, manganese, and molybdenum in oats grown on 13 soils from different parts of Australia. Their findings differ from those of Wood and Sibly for zinc. The mean net export of zinc from leaves was 34 per cent, and all but two soils showed the effect.

Bergh (1952) added Zn^{65} to soil around plants of *Pisum sativum*. After 36 days, 1.04 per cent of the radiozinc had been absorbed and was distributed in the plants as follows: pea, 0.19 per cent; shell, 0.16; flower, 0.01; blade, 0.27; stem, 0.11; and root, 0.30.

3. *Deficiency Levels in Plants*

The reported zinc content of plants at which zinc deficiencies occur varies somewhat. Finch and Kinnison (1933) found that leaves of healthy pecan trees contained from 13 to 16 p.p.m. of zinc. Rosetted leaves contained only 3 to 4 p.p.m. Zinc deficiencies in tung have been reported for trees with leaves containing less than 10 p.p.m. (Drosdoff, 1943). In 1950 Drosdoff reported slight symptoms when tung leaves contained 26 p.p.m. Deficient apple leaves in British Columbia were found to contain from 3 to 20 p.p.m. of zinc, and healthy leaves contained 6 to 40 p.p.m. (Woodbridge, 1951).

Zinc-deficient alfalfa plants in Washington averaged 8 p.p.m. in the tops, and normal plants contained an average of 13.8 p.p.m. (Boawn and Viets, 1952). Viets *et al.* (1953) also reported that a zinc level of 15 p.p.m. in the leaf of corn from the second node below the ear at silking was adequate for 100 to 125 bushel yields. The zinc content of selected parts of annual crops in Washington showing zinc deficiency ranged from 9 to 22 p.p.m. (Viets *et al.*, 1954b). Viets *et al.* (1954a)

reported that zinc deficiency symptoms occurred when mature bean leaves contained 20 p.p.m. or less of zinc. Zinc deficiency appeared in oats with leaves containing less than 20 p.p.m. (Wood and Sibly, 1950).

Klosterman and Clagett (1956) found that the zinc content of potato leaves in North Dakota ranged from 13 to 87 p.p.m. Although visible symptoms of zinc deficiency were usually lacking, they considered plants containing less than 30 p.p.m. as likely to show some response to foliar applications of zinc.

Data are not sufficient to establish critical zinc levels for plants. No doubt the level at which response may occur varies somewhat in even the same crop variety, depending on other nutritional or environmental factors. Also, in only a few cases were tests made in apparently normal plants to determine whether those testing low in zinc would respond to treatment. Apparently plants with leaf zinc contents below 15 p.p.m. can be suspected of zinc deficiency.

V. Functions of Zinc in Higher Plants

1. *Auxin Relations*

Retarded stem elongation, small, narrow leaves, and misshapen fruit associated with zinc deficiency led Skoog (1940) to investigate relations between the deficiency and auxin production. He could find no auxin activity in stems of deficient tomato and sunflower plants and very reduced activity in the leaves. Auxin activity was reduced 50 per cent or more before there were signs of diminished growth. When zinc was added to severely affected plants, auxin content increased greatly in one to a few days. The failure of auxin production seemed to be specific with zinc deficiency, since Skoog could find no effect of copper and manganese deficiencies on auxin production preceding growth reduction.

According to Hoagland (1944) Stout observed in an experiment that tomato plants in a low zinc solution reached a point under good natural illumination where growth failed. When these plants were taken into the laboratory with less intense light, growth was resumed without further addition of zinc. These results paralleled the observations of Chandler (1937) that zinc deficiency symptoms of citrus are most in evidence on the south sides of trees.

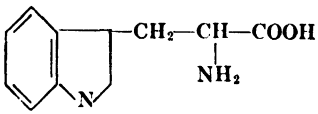
Went and Thiman (1937) have shown that high light intensity and particularly light of short wavelength inactivates auxin. On the basis of this relationship Skoog (1940) grew tomatoes under colored light filters in solutions deficient in zinc. Plants under red light grew almost as tall as the controls supplied with zinc and their auxin content

was almost normal. Similar plants under blue light showed much less growth. Addition of 3-indoleacetic acid to the culture medium or spraying it on the leaves of zinc-deficient plants increased stem growth during early deficiency stages, but the acid did not replace zinc as a nutrient. The effect seemed to be on the utilization of available zinc rather than substitution for the auxin lost from the stem.

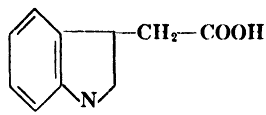
Skoog (1940) further demonstrated that zinc-deficient plants inactivated 3-indoleacetic acid more rapidly than control plants. He postulated that auxin destruction in deficient plants resulted from an increase in peroxidase activity. Reed (1946) has in part substantiated this theory by showing that phenoloxidase activity increases and dehydrogenase activity decreases with zinc deficiency in plants. Further, Nason *et al.* (1952) reported that zinc deficiency in tomatoes doubled ascorbic acid oxidase and increased polyphenol oxidase and peroxidase from two to six times. The findings of Tsui (1949) are in opposition to the concept of higher oxidase activity associated with zinc deficiency. Using the Warburg technique he could find no evidence that zinc plays any direct part in the respiratory system of higher plants.

The role of zinc in auxin relations of plants has been further clarified by Tsui (1948a). He confirmed the findings of Skoog in relation to the reduction in auxin content of zinc-deficient plants and further showed that the decrease in auxin applied to bound auxin as well as to free auxin. On the basis of the findings of Boysen-Jensen (1932) that auxin is formed from tryptophan by *Aspergillus niger*, he studied the tryptophan content of tomato plants in relation to zinc deficiency. Zinc-deficient plants contained significantly smaller amounts of tryptophan than the control, even before there were visible symptoms of zinc deficiency. Three days after zinc addition there was a noticeable increase in tryptophan content. Leaves from the apical parts contained the most tryptophan and those from the base, the least. Zinc and tryptophan in the tissues followed a similar course, but the maximum for tryptophan preceded that of auxin. Tsui concluded that zinc is required directly for the synthesis of tryptophan and that auxin is produced from the tryptophan.

Wildman *et al.* (1947) have shown that indoleacetic acid is enzymatically produced in plants from tryptophan. In their studies relatively large amounts of indoleacetic acid were formed in leaves infiltrated with solutions of tryptophan and allowed to incubate for short periods under aerobic conditions. Bonner (1950) postulated that indoleacetic acid is produced from tryptophan with indoleacetaldehyde as an intermediate. However, the steps in the process have not been fully determined. The relationships between tryptophan and indoleacetic acid are shown by their formulas:



Tryptophan



Indoleacetic acid

The role of zinc in tryptophan formation needs clarification. Hoagland (1944) cited studies by Bean (1942), wherein incipient stages of zinc deficiency in tomato plants markedly retarded protein and starch synthesis. Nitrate accumulated in zinc-deficient plants, continued proteolysis occurred, and amino acids and amides accumulated. Zinc deficiency occurred when plants were fed either nitrate or ammonia nitrogen, indicating that nitrate reduction was not the only role of zinc in nitrogen metabolism. Wood and Sibly (1952) also found that proteolysis occurred in zinc-deficient plants and that addition of zinc resulted in protein synthesis in the leaves.

Nason *et al.* (1950) reported that the enzyme catalyzing the synthesis of tryptophan from serine and indole is completely absent in zinc-deficient plants.

Wood (1953) reasoned that the failure of tryptophan and protein synthesis in zinc-deficient plants could be attributed to the destruction of pyridoxal phosphate. This concept was based on the following evidence: (*1*) The synthesis of tryptophan from serine and indole requires pyridoxal phosphate as a coenzyme (Umbreit *et al.*, 1946). (*2*) According to Reed (1946), accumulations of inorganic phosphate increase phosphatase activity in zinc-deficient plants. (*3*) Sadisvan (1950) presented evidence that phosphatase of *Penicillium chrysogenum* contains zinc, and work in his laboratory has shown that zinc-deficient tomato plants possess high phosphatase activity towards glycerophosphate and that zinc treatment decreases phosphatase activity. High phosphatase activity could result in hydrolysis of hexosephosphates and adenosine triphosphate with resulting reduction in activity of the glycolytic and respiratory cycles. This could cause decreased synthesis of amino acids and result in reduced nitrate reduction if the latter is linked through these cycles to hydrogen and energy transfers. Further work will be needed to check this line of reasoning.

2. *Other Functions of Zinc in Plants*

Some effects of zinc deficiency on plants are apparently incident to the reduction in auxin content. Leaves of zinc-deficient plants are often lower in moisture content than normal leaves. Tsui (1948b) found that the water content and growth of plants changed simultaneously with zinc deficiency. Within 2 days after zinc was added to deficient plants

the water content of the plants had increased and growth was resumed. The osmotic pressure of the sap of the tops of zinc-deficient plants ranged from 5 to 9 atmospheres, whereas that of the controls varied from 5 to 6 atmospheres. The changes in water content were directly related in time to changes in auxin content, as reported by the same worker (1948a). These findings tie in with the report of Skoog *et al.* (1938) that the application of indoleacetic acid to decapitated stems caused an increased uptake of water and salt. Also, Van Overbeek (1944) showed that auxin increased the uptake of distilled water by potato discs. Apparently the increased water in tissues in the presence of auxin does not result from water moving against a concentration gradient but results from the action of auxin under aerobic conditions in causing a loosening of the cell wall which allows the cell to take up water and expand osmotically (Orden *et al.*, 1956; Cleland and Bonner, 1936).

Most descriptions of zinc deficiency of fruit trees point out the early abscission of leaves on all but the terminal buds of branches. Gaur and Leopold (1955) found that auxin prevents leaf abscission when present in abundance and that low auxin concentrations promote abscission. Some of the major visual symptoms of zinc deficiency are, therefore, apparently directly related to the vital role of zinc in auxin production in plants.

The chemical relationship between niacin and tryptophan suggests that niacin formation, like auxin, might be reduced in zinc deficiency. A brief report by Crane (1954) indicated no effect of zinc deficiency on the niacin content of tomato plants.

Zinc plays a role in the production or functioning of several enzyme systems in plants but the interrelationships involved have not been clarified.

Carbonic anhydrase which catalyzes the reaction $H_2CO_3 \rightarrow H_2O + CO_2$ has been reported as containing zinc. This enzyme has been found in animal tissues, and recently Day and Franklyn (1946) and Bradfield (1947) have reported its presence in leaves of several green plants. Many of the plants shown to contain the enzyme are especially susceptible to zinc deficiency. Wood and Sibly (1952) found that carbonic anhydrase is confined to the nonchloroplast fraction of oat leaves. The carbonic anhydrase content of tomato and oat plants varied directly with zinc content. Day and Franklyn (1946) reported that zinc is associated in a nondialyzable form with the protein of the enzyme, but a functional relationship was not proved. Wood and Sibly (1952) concluded that the low content of this enzyme in zinc-deficient plants results from a blocking of metabolic reactions leading to the formation of an essential protein associated with the enzyme.

Johnson (1941) and Berger and Johnson (1939) found that yeast and *Aspergillus parasiticus* tripeptidases were activated by zinc.

Aldolase catalyzes the splitting of hexose diphosphate molecules into two molecules of triosephosphate—an important step in the respiratory breakdown of carbohydrates. The enzyme occurs widely in plant tissues. Apparently the enzyme contains no heavy metals, but in tests by Quinlan-Watson (1951) aldolase activity was found to fall sharply with zinc deficiency. Addition of zinc to the medium resulted in increased enzyme activity.

Although the one report relating aldolase and zinc needs further investigation, the relationship suggests an explanation for the frequently reported disturbed carbohydrate metabolism in zinc deficiency. Thus Haas (1936) reported that zinc deficiency in orange leaves resulted in an increase in total sugar and particularly in nonreducing sugars in both healthy and mottled cuttings. Also Eltinge and Reed (1940) found that zinc deficiency of excised tomato roots resulted in the complete absence of starch and the accumulation of abnormal quantities of calcium oxalate, tannins, and fat.

Shear (1953) has reported that high zinc nutrition along with ample potassium fertilization reduced cold injury to one-year-old tung trees. According to a report by Bahrt *et al.* (1944) zinc sulfate treatment of soil where zinc deficiency symptoms were not apparent had no well-defined influence on the oil content of tung fruit.

Mulder (1948) concluded that zinc is not of major significance in nitrogen fixation, since nodules were formed and nitrogen was fixed when pea plants were abnormal as a result of zinc deficiency.

A few papers deal with the relationships between zinc nutrition and disease resistance of plants. The limited data available seem inadequate, however, to support any generalizations. Millikan (1938) reported markedly less damage to wheat from root fungi and eelworms (*Heterodera schachtii*) on plots receiving zinc sulfate treatments than on control no-zinc plots. Smith (1951) found no difference in the disease susceptibility of plants receiving low and high zinc nutrition in solution culture studies with tomatoes. Yarwood (1954), on the other hand, found that dipping bean leaves in 0.001 to 0.03 per cent zinc sulfate or 0.1 to 1 per cent calcium chloride solutions following inoculation with tobacco mosaic virus resulted in increased lesions compared with leaves dipped in distilled water. Similar treatments with zinc decreased the lesions on *Nicotiana glutinosa*.

VI. Zinc Toxicity

Agriculturists were aware of the toxicity of zinc to plants before they knew it was essential. In 1904 Haselhoff and Gossel reported that

zinc sulfate was highly injurious to wheat. Meyer in 1905 found that crop yields were much greater in earthenware than in zinc pots and that the injurious effects were largely overcome by liming. In 1908 Ehrenberg reported burying zinc plates in soil with resulting injury to plants. Conner (1920) found that paraffin coatings over galvanized pots failed to protect plants against zinc toxicity. A similar damage from zinc to forest nursery seedlings grown in galvanized iron tubes was described by Hawkins and Cameron (1953) as a severe iron deficiency chlorosis.

The small difference between adequate and toxic zinc is illustrated in the report of Roberg (1932) that 0.001 mg. zinc per 100 ml. solution stimulated chlorella, whereas 0.005 mg. retarded growth. Gall and Barnette (1940) found that replaceable zinc in milliequivalents per 100 g. of soil became toxic for corn between 0.688 and 1.376 on a Norfolk sand, between 0.758 and 1.137 on an Orangeburg fine sandy loam, and between 1.615 and 2.153 on a Greenville clay loam. The values for cowpeas were appreciably lower. Calcium carbonate reduced the toxicity.

The most recent studies on zinc toxicity are in the area of the interference of micro nutrient elements with iron absorption. The effectiveness of several elements in producing iron deficiency chlorosis of oats in studies of Hunter and Vergnano (1953) was in the order:

$$\mathrm{Ni} > \mathrm{Cu} > \mathrm{Co} > \mathrm{Cr} > \mathrm{Zn} > \mathrm{Mo} > \mathrm{Mn}$$

In producing iron deficiency in beets (Hewitt, 1951) the elements Cd, Cu, Co were highly effective, and Ni, CrO_4, Zn, Cr, Mn were less effective, in the order listed. Similarly, Smith and Specht (1953) found that copper, zinc, and manganese interfered with iron metabolism and induced iron chlorosis of citrus seedlings growing in vermiculite solution cultures. The effects were produced by 0.1 p.p.m. Cu, 3 p.p.m. Zn, and 5 p.p.m. Mn.

The roles of copper and manganese in inducing iron chlorosis have received far more attention than that of zinc. One concept that has much support is competition of the metals for organic complexes in plants. Hewitt (1951) pointed out that the order of toxicity of metals is reasonably close to the order of stability of metal organic complexes:

$$\mathrm{Cu}^{++} > \mathrm{Na}^{++} > \mathrm{Co}^{+++} > \mathrm{Fe}^{+++} > \mathrm{Zn}^{++} > \mathrm{Cd}^{++} > \mathrm{Fe}^{++} > \mathrm{Mn}^{++} > \mathrm{Mg}^{++}$$

VII. Zinc Content of Soils

The content of total zinc in soils is generally low in comparison with other essential elements. The data on zinc and other trace elements in soils have been rather thoroughly reviewed by Swaine (1950).

He cited more than 70 papers containing information on the amount of total or extractable zinc in various soils. He gives an average value of 80 p.p.m. for zinc in the lithosphere. Most mineral soils cited contained between 10 and 300 p.p.m. of total zinc, although one soil was reported with a content of 16 per cent. Staker and Cummings (1942) found that peat soils of New York state contain from traces to as high as 23,600 p.p.m. of zinc.

Exchangeable zinc (Swaine, 1950) is usually less than 1 p.p.m. Numerous data are also summarized by Swaine on zinc removed from soils by a number of different extracting reagents ranging from strong acid digestions to leaching with water or neutral salt solutions.

Hibbard (1940b) found that zinc in California soils was much more concentrated near the surface than below. This concentration was greatest in soils that had accumulated organic matter from leaf fall and other plant residues for long periods. He concluded that zinc is enriched in the surface soil by vegetative residues and that this may be a major factor in zinc deficiencies of deep-rooted plants.

Thorne *et al.* (1942) found the zinc content of a number of Utah soils varied from 30 to 250 p.p.m. Invariably total zinc was greatest in the surface horizons and decreased with depth. Wright *et al.* (1955) studied the distribution of several minor elements in virgin profiles of soils of several great soil groups. Relative to sesquioxides, zinc accumulated in the A_0 and B horizons of Podzol and Brown Podzolic soils and in the A_1 horizon of Brown Forest soils. In general zinc displayed little tendency to leach, and soil accumulations were closely associated with residues of organic materials.

Some variations of soil zinc have been associated with parent materials. Thorne *et al.* (1942) found that soils formed from limestone contained more zinc than soils formed from gneiss or quartzite, even though samples of parent rock contained similar amounts. Shiha (1951) found that in soils near Uyeda City total zinc is greater in recent alluvial soils than in shales.

Vlasyuk and Zimina (1954) reported that the content of available zinc in soils of Russia is related to the zinc content of the parent rocks. The distribution of zinc in genetic horizons of soil profiles followed closely the redistributions of colloids. In most cases the available zinc was higher in the illuvial horizon than in the parent rocks. Like Hibbard (1940a), these workers found the surface of undisturbed forest soils greatly enriched with zinc through decomposition of fallen foliage.

VIII. Factors Affecting Available Zinc in Soils

Although the total zinc content of soils is moderately low, plants need such small quantities that zinc deficiencies would be rare if total

soil zinc were even moderately available to plants. Plants are generally adequately supplied with zinc in nutrient solutions containing 0.1 p.p.m. or more of zinc (Brown and Wilson, 1952; Wilson, 1953). In consequence the insolubility of zinc in soils has stimulated a number of studies.

1. pH

Numerous investigators have noted that zinc deficiencies usually occur on soils of pH 6.0 or higher. In an early field study related to pecan rosette Alben and Boggs (1936) found some zinc deficiency on soils more acid than pH 5.5 but explained this on the basis of a very low total zinc content. Deficient soils between pH 7.4 and 8.5 contained adequate total zinc but its availability was low. Camp and Reuther (1937) observed that zinc deficiency can be expected in citrus groves if the pH reaches 6.0 or above. Camp (1945) concluded "It seems fairly well established that the availability of zinc declines as the pH of the soil rises, the critical point being between the pH range of 5.5 to 6.5."

Lott (1938) showed that zinc toxicity is eliminated by the addition of calcium carbonate to a soil to bring it to pH 6.0 or above. He found minimum uptake of zinc by oat seedlings at a pH of 6.5. Wear (1956) found that the addition of 1 ton per acre of calcium carbonate to Norfolk sandy loam decreased the zinc content of sorghum. The pH increased from 5.7 to 6.6. In adjacent plots treatment with calcium sulfate decreased the pH from 5.6 to 4.8 and increased zinc in sorghum.

Peech (1941) found that soil zinc extractable with normal NaCl increased with decreasing soil pH. Epstein and Stout (1951) analyzed supernatant solutions from a series of bentonite cultures of uniform total zinc content and found an increasing amount of soluble zinc with increasing hydrogen-ion concentration. Similar observations on the occurrence of zinc deficiencies in soils in the range of pH 6.0 to 8.0 have been made by Chandler (1937); Thorne and Wann (1950); Woltz *et al.* (1953); Shaw and Dean (1952); and Greenwood and Hayfron (1951).

Zinc, like several other metals, forms a hydroxide with ability to act as a base or weak acid depending on the pH of the liquid environment. The formation of negatively charged zincates was suggested by Camp (1945) as being significant in soils more alkaline than pH 7.85.

Two types of zincate ions have been shown to exist (Hildebrand and Bowers, 1916; Berheim and Quintin, 1950). The acid zincate, $HZnO_2^-$, is the prevalent form in lower concentrations of alkali, and the zincate ion, $ZnO_2^{=}$, is the principal form as the alkali concentration is increased. These simplified formulas for zincates should be replaced, however, by a complex grouping in accord with Werner's coordination

theory to give a zinc a coordination number of six in an alkali solution (Thorne and Roberts, 1948).

$$\left[\begin{array}{ccc} OH & OH & OH \\ \searrow & \downarrow & \swarrow \\ & Zn & \\ \nearrow & \uparrow & \nwarrow \\ OH & OH & OH \end{array}\right]^{=}$$

Similar complexes may also be formed with four ammonia ions in coordination bonding around the zinc ion.

Berheim and Quintin (1950) through polarographic studies found evidence of an equilibrium status for zincate, zinc, and hydroxyl ions in alkali solutions. They obtained a K_2 value of 0.83×10^{-16} for the mass action equation.

$$\frac{[Zn^{++}][OH]^3}{[ZnO_2H^-]} = K_2$$

Jurinak and Thorne (1955) reported titration curves with alkali hydroxides for dilute solutions of zinc in equilibrium with bentonite clay. The curves obtained by titrating clay suspensions, containing zinc equivalent to 1.0 per cent of the cation exchange capacity of the clay, with NaOH and $Ca(OH)_2$ are reproduced in Fig. 2. The curves for NaOH and KOH were similar.

The increased solubility of zinc with NaOH additions as the pH exceeded 6.5 was taken as evidence of the formation of soluble zincate ions. An absence of increased zinc solubility in the alkaline range with $Ca(OH)_2$ additions is consistent with the low solubility of calcium zincates. Since under conditions favorable for plant growth calcium is a major cation constituent of soil solutions, the above data indicate that zincate formation is probably not an important factor in increasing zinc availability in nonalkali soils within the alkalinity range favorable for plant growth.

The predominant occurrence of zinc deficiencies in the pH range of 6.0 to 8.0 is favored by conditions of minimum zinc solubility.

In Fig. 2 the minimum concentration of zinc in solution with the sodium hydroxide titration was about 1 microgram per gram of clay. Since in the experimental procedure the gram of clay was suspended in about 50 ml. of solution, the actual concentration of zinc in solution would be 0.02 p.p.m. This is less than the 0.1 p.p.m. reported needed for normal growth in solution cultures, but would probably be adequate for plants when continuously replenished under equilibrium soil conditions.

2. *Precipitation by Phosphates*

Zinc deficiencies frequently occur in soils containing abnormally high contents of soluble or total phosphates. In some instances phos-

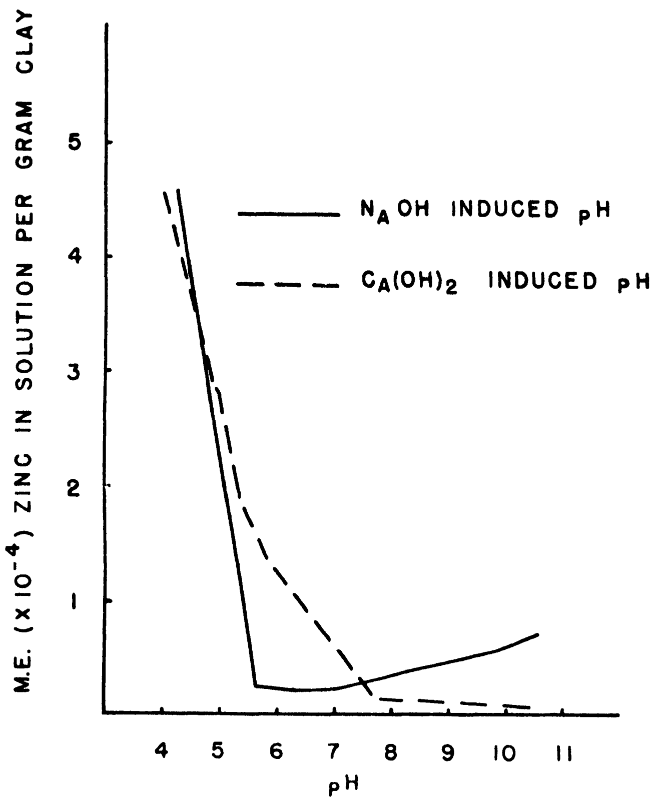


FIG. 2. Zinc in solution as a function of sodium hydroxide and calcium hydroxide induced pH values. Zinc present at 1 per cent of cation exchange capacity of bentonite clay present in suspension. (Figure adapted from data of Jurinak and Thorne, 1955.)

phate fertilizer applications have induced zinc deficiencies; in other instances such treatments have not done so.

In an early study on the zinc deficiency of tung trees in Florida, Mowry and Camp (1934) concluded that high phosphate in soils was an important factor in reducing available zinc. In California zinc deficiencies commonly occur on old corral spots (Chandler, 1937), and these soils frequently contain large amounts of soluble phosphate. Similarly in Utah (Thorne and Wann, 1950) zinc-deficient soils tested were uniformly high in soluble phosphate. Zinc deficiencies of corn are common in the high phosphate soils of central Tennessee, particularly in association with lime treatments (Winters and Parks, 1955).

West (1938) reported that zinc deficiency symptoms of citrus occurred on superphosphate-treated plots in Australia, apparently being induced by the phosphate ion. Rogers and Wu (1948) found that

phosphate applications to virgin Lakeland fine sand decreased the zinc content of oats, reaching a constant value beyond which further phosphate treatment had no effect.

Leggett (1952) added radioactive labeled zinc to three soils and studied the effects of additions of varying amounts of phosphate on zinc uptake by plants. The zinc content of bean plants was reduced from 20 to 30 per cent and that of corn by 30 to 50 per cent in the three soils by addition of up to 800 pounds of P_2O_5 per acre. No zinc deficiency symptoms occurred. Similar results were obtained by Bingham and Martin (1956). They added varying amounts of monocalcium phosphate to three California soils and found that the copper and zinc contents of citrus plant leaves were reduced. Copper deficiency symptoms were induced but no signs of zinc deficiency were observed.

Chapman *et al.* (1937) were able to produce zinc deficiency symptoms of citrus in solution cultures and to change the degree of mottling in the leaves by changing the phosphate concentration in the solutions. The high concentrations of phosphate increased the degree of mottling.

Morrill (1956) measured zinc uptake by corn from solution cultures of varied pH, controlled in one series by KH_2PO_4-NaOH buffers and in another series by barbital-HCl buffers. Throughout the pH range of 6.5 to 8.5 the zinc uptake was significantly less in the presence of the phosphate.

In further support of a role of phosphate in zinc unavailability Staker (1942) obtained greater reduction in zinc toxicity in peat soils by addition of phosphate than by any other treatment, including liming to a higher pH. These soils contained as much as 10.16 per cent zinc.

Other workers who report that phosphate may decrease the availability of zinc include Powers and Pang (1947), Millikan (1947), and Loneragen (1951).

In contrast to the results of the several studies cited Boawn *et al.* (1954a) failed to influence the uptake of either applied or native soil zinc by beans through the application of superphosphate to soils in the Columbia Basin area of Washington. No effect of phosphate on zinc uptake occurred even though soil applications as high as 400 pounds of P_2O_5 per acre were made and the phosphorus contents of the bean plants were doubled.

The author has also been unable to increase zinc deficiency symptoms of peach trees by applications of superphosphate equivalent to a ton of soluble P_2O_5 per acre. These treatments were made in an orchard where mild zinc deficiency symptoms were general (unpublished data).

Jamison (1944) reported the solubility of zinc in a phosphate solution to be 2.5 p.p.m. at pH 7.0 and 3.5 p.p.m. at pH 8.0. Below pH 7.0 and above 8.0 zinc solubility increased markedly. The phosphate-ion

concentration of the solutions was not reported. However, zinc solubility would be decreased as phosphate concentration in solution increased. Consequently, although phosphate in soils would oppose zinc solubility, it is doubtful whether zinc deficiency can be explained by direct precipitation of zinc by phosphate ions.

3. *Organic Matter and Microorganisms*

Under field conditions zinc deficiencies often occur where there have been barnyards or old corrals. In Utah (Thorne and Wann, 1950), zinc-deficient orchards usually have been fertilized for many years with liberal applications of farm manure, and have also usually been clean cultivated. Chandler (1937) reported that four annual applications of 60 tons of fresh horse and cow manure to the acre or the equivalent amount of nitrogen, phosphorus, or potassium did not produce zinc deficiency symptoms on healthy trees or grapevines.

Ark (1936) found that sterilization of a zinc-deficient soil with steam, formalin, or ether caused corn and seedlings of apricots and walnuts to make as good growth as when treated with zinc sulfate. But reinoculation of the soil with unsterilized soil or with cultures of two different strains of bacteria isolated from the untreated soil resulted in the plants' showing typical zinc deficiency symptoms. Hoagland *et al.* (1937) obtained similar results in preventing zinc deficiency of corn by sterilizing a soil by either autoclaving or treating with formalin. Strangely enough, these early studies have apparently received no further attention, and it is not possible to determine whether the beneficial effects of sterilization came from a release of available zinc, from a reduction in microbial competition for the zinc present, or from other factors.

Baughman (1956) has furnished considerable support for Hibbard's thesis that organic matter may be a major soil factor in zinc fixation. Two thirds of the zinc in a sample of Maumee soil and one-half in a Floyd soil of Indiana were associated with organic matter. The zinc fixing power of the two soils was in the order of their organic matter content. Zinc retained by organic matter was designated as chelated and complexed. Chelated zinc was interpreted as that extractable with copper acetate. Complexed zinc was designated as that which was not extractable by either copper or ammonium acetate but which was released by oxidation of the organic matter with hydrogen peroxide. The results indicate that chelation and complexing of zinc by organic matter may also be a significant factor in reducing zinc availability in soils.

DeMumbrum and Jackson (1956b) also concluded that peat may hold zinc and copper by a chelation type of reaction. Their evidence

was based on infrared absorption studies which showed considerable shifts in the double bond region of peat sorbing zinc or copper which were not apparent when sorbing calcium and related strong basic cations.

Although the evidence indicates that zinc may be absorbed or complexed by organic matter, at least two groups of workers, Hibbard (1940a) and Tucker and Kurtz (1955), failed to obtain significant releases of zinc in several soils by oxidation of organic matter with hydrogen peroxide. Tucker and Kurtz concluded that "the amounts of zinc released by peroxide treatment were generally small and do not indicate that a large proportion of the soil zinc is in the organic form."

4. Adsorption

Zinc has been found adsorbed in small amounts on the colloids in most soils. Elgabaly and Jenny (1943) investigated the adsorption and fixation of zinc on montmorillonite clays. They concluded that zinc adsorption from zinc chloride solutions involves the ions Zn^{++}, $(ZnCl)^{+}$, and $(ZnOH)^{+}$ but that the release of zinc from zinc-clay by sodium chloride and calcium chloride is restricted mainly to divalent zinc. Some of the zinc adsorbed could not be replaced with salt solutions.

In an extension of the above studies Elgabaly (1950) found that zinc adsorbed by bentonite, kaolinite, pyrophillite, muscovite, biotite, vermiculite, brucite, and talc is not all exchangeable. In bentonite, kaolinite, pyrophyllite, muscovite, and biotite, zinc adsorbed and not readily replaced by other cations decreased the ammonia adsorption capacity. This was interpreted as the zinc being adsorbed in unfilled holes in the octahedral layer of aluminosilicates. In clays containing magnesium, including magnesium bentonite, vermiculite, and brucite, zinc fixation did not decrease the ammonia adsorption capacity. The latter results were interpreted as zinc replacing magnesium ions in the exposed lattices of the clay particle surfaces.

The fixation of zinc in clay lattices is further supported by the investigations of Nelson and Melsted (1955). They added Zn^{65} to soils and clays with different exchangeable ions and measured zinc adsorption. The data indicated that zinc retention by soils has the following relation to other cations:

$$H > Zn > Ca > Mg > K$$

Zinc added to hydrogen soil systems could be nearly all replaced with ammonium acetate. Part of the zinc added to calcium soil systems could not be replaced by ammonia. This zinc could be removed by extraction with HCl. The proportion of acid-extractable zinc increased with length of contact and with decreasing concentrations of the zinc additions. As

with Elgabaly's findings, the strongly fixed zinc had no appreciable effect on the cation exchange capacity. Brown (1950) observed similar fixation of zinc by clay.

DeMumbrum and Jackson (1956b) found that montmorillonite sorbed about 10 per cent more zinc and copper than of cations which form strong bases and that a peat sorbed 40 per cent more. Infrared absorption studies indicated that copper and zinc reacted in part with OH groups in the silicate layers of the crystal lattice.

Liming of acid soils has frequently induced zinc deficiencies. Woltz *et al.* (1953) found that applications of ground limestone resulted in greater fixation of zinc in soil than did applications of phosphate fertilizer. Winters and Parks (1955) found that liming the high-phosphate soils of central Tennessee favored zinc deficiency of corn.

Zinc deficiencies are common in calcareous soils, and Leeper (1952) postulated that calcium carbonate may act as a strong absorbent for heavy metals.

Canals *et al.* (1949, 1950) studied the adsorption of zinc from solution onto finely powdered calcium carbonate. Zinc adsorption increased with temperatures above and below 57° C., and copper ions reduced the adsorption of zinc ions.

Jurinak and Bauer (1956) used isotopic tracer techniques to study zinc adsorption on calcite, dolomite, and magnesite at concentrations of zinc within the solubility of $Zn(OH)_2$. Zinc was adsorbed most strongly on magnesite, to an intermediate degree on dolomite, and least strongly on calcite. Thermodynamic data and calculations showed that the reaction of zinc with calcite was distinctly different from reactions with dolomite and magnesite. The evidence indicated that zinc is adsorbed in the crystal surfaces of dolomite and magnesite at sites in the lattice that might normally be occupied by magnesium. Entropy data supported the concept that the zinc ion is stripped of water of hydration on being absorbed by dolomite and magnesite but that such an energy change does not occur on adsorption on calcite. The similarity of ionic radii of zinc and magnesium, 0.83 A. and 0.78 A., respectively (Evans, 1948), further supports the concept of zinc's occupying magnesium sites.

The close relationship between zinc and magnesium in adsorption is in agreement with the findings of Merrill *et al.* (1953) wherein soil treatment with magnesium increased the zinc content of tung leaves and soil treatment with zinc increased the uptake of magnesium.

The strong adsorption of zinc on soil minerals, often within the crystal lattice, offers the best explanation for its low solubility and frequent low availability in soils. The strong power of zinc adsorption by solid surfaces is again illustrated by a recent paper of DeMumbrum and Jackson (1956a) showing that calcium-montmorillonite and cal-

cium-peat can accumulate zinc ions from very dilute solutions in equilibrium with such relatively insoluble compounds as ZnO, $Zn(OH)_2$, and $Zn_3(PO_4)_2$. These results support the findings of Jurinak and Bauer (1956).

The studies on zinc solubility in soils are in agreement with the general tendency of this element to form many compounds of low solubility. Precipitation of zinc as the hydroxide, carbonate, or phosphate can reduce soluble zinc in soils to low levels, but the few data available indicate that such reactions do not satisfactorily account for the extremely low concentrations required to induce zinc deficiency. Present evidence indicates that adsorption reactions can reduce zinc solubility to deficiency levels. Such adsorption reactions can occur on many types of surfaces including clay minerals, organic matter, and lime minerals. Data indicate that the strongest adsorption of zinc on crystal lattices is associated with surfaces that contain magnesium ions.

IX. Methods of Zinc Determination

There is a voluminous literature on methods of zinc analysis. No attempt will be made to review this material. This brief review is confined to the presentation of a few general references giving helpful information on procedures in common use for the determination of zinc in soils and plant materials.

Total zinc has been brought into solution from soils for analysis by fusing with potassium pyrosulfate (Boggs and Alben, 1936) and by dissolving the fusion mixture in a hydrochloric acid solution. Plant materials have been digested with nitric, sulfuric, or perchloric acids (Piper, 1944), or ashed and the residue taken up in an acid solution (Hibbard, 1937).

1. Colorimetric Procedures

Until the development of the dithizone method small amounts of zinc were usually estimated turbidometrically after precipitation as either the sulfide or the ferrocyanide (Snell and Snell, 1949). The reagent diphenylthiocarbazone, usually called dithizone, was first developed in 1878 by Emil Fischer and shown to form colored complexes with several metals. The reagent was not employed for analytical use, however, until after the studies of H. Fischer in 1925 (Sandell, 1944).

Dithizone gives a series of brilliantly colored complexes with gold, platinum, palladium, silver, mercury, stannous, bismuth, copper, zinc, cobalt, nickel, lead, thallium, and cadmium ions. The various complexes can usually be separated to give the color due to a single ion or the dithizone equivalent to it. Zinc forms a red complex with dithizone in

an alkaline solution. This can be separated from the aqueous solution by shaking with carbon tetrachloride or chloroform. Procedures for separating zinc from other metals and determining the amounts present by the dithizone procedure have been reviewed by Snell and Snell (1949), Sandell (1944), and Piper (1944).

Rush and Yoe (1954) have recently proposed another sensitive reagent for zinc determination, 2-carboxy-2′-hydroxy-5′-sulfoformazylbenzene. This reagent is now marketed under the trade name of Zincon. Zinc and copper form blue complexes with the reagent which can be separated by proper adjustment of the pH.

2. *Polarographic Procedures*

The sensitivity of zinc determination by the polarograph is comparable to that by the colorimetric dithizone method. Usually the dithizone procedure is used to separate zinc from other interfering metals, although cadmium, lead, and copper can be read on the same voltage curve unless these other elements are present in concentrations greatly exceeding the concentrations of zinc. General polarographic procedures have been described by Kolthoff and Lingane (1952). Methods for the polarographic determination of zinc in plants have been published by Reed and Cummings (1940) and Walkley (1952).

3. *Spectrographic Procedures*

Zinc gives only relatively weak lines in the spectrograph, and these are in the short wavelength region (2138.5 A. and 3345.0 A.). For these reasons it is frequently necessary to concentrate zinc in plant ash or to use special sensitized film. Discussions and procedures on spectrographic determination of zinc have been prepared by Mitchell (1948) and Stiles (1946).

X. Soil Tests for Available Zinc

1. *Chemical Tests*

As with other elements essential for plants, considerable effort has gone toward devising soil tests that will differentiate soils containing inadequate available zinc for normal plant growth. Hibbard (1940a) developed an extracting reagent consisting of a 0.5 *M* KCl solution adjusted to pH 3.2 with acetic acid. A 5-g. sample of soil was extracted with 400 ml. of the solution, and zinc in the extract was determined by the dithizone method. About 140 samples of soil and rocks collected from central California were tested by the procedure (Hibbard, 1940b). The extracted zinc from the samples was usually in the range of 1 to 5 p.p.m. In a later modification of the method Hibbard (1943) found

that extending the extracting period from a few hours to several days improved the relation between extracted zinc and uptake by plants.

Wear and Sommer (1947) used the method of Hibbard with a shorter procedure (Alexander and Taylor, 1944) for zinc determination by the dithizone method. The shorter method gave as satisfactory a relation to zinc deficiency symptoms as did the longer method of Hibbard.

Thorne *et al.* (1942) working with Utah soils found no consistent correlations between any of the factors: total zinc, zinc extracted by Hibbard's method, organic matter content, or pH. They concluded that total zinc differentiated zinc-deficient soils as well as the extraction procedure of Hibbard.

Bergh (1947, 1948) extracted 20 to 30 g. of soil by shaking for 1 hour with 200 to 300 ml. of 0.1 N $MgSO_4$ with the pH of the extracting solution adjusted to that of the original soil. Zinc content of the extracts reflected previous soil treatments with zinc sulfate. Zinc deficiency was reported to occur in wheat and barley when extractable zinc values for the soil were 3.5 and 6.6 p.p.m., respectively. Doubtful deficiencies occurred with values of 3.1 for rye and 3.6 for oats. Highest yield of wheat occurred when extractable zinc was 160 p.p.m.; rye, 40; barley, 95; and oats, 480.

Viro (1955) extracted Finnish forest soils with a solution of ethylenediamine-tetraacetic acid (a chelating agent for heavy metals). He obtained a good correlation between the amounts of calcium, copper, and zinc removed in the extract and the fertility status of the soil. No indications were given that any of the vegetation growing on the soils showed zinc deficiency.

Shaw and Dean (1952) extracted soil samples with a two-phase system of aqueous ammonium acetate and carbon tetrachloride containing dithizone. The procedure was applied to about 50 samples of soil collected from various zinc-deficient areas of the United States. They obtained a good relationship between extracted zinc and the incidence of zinc deficiencies in crops.

2. *Aspergillus niger* Test

Many early zinc investigators found that the common soil fungus, *Aspergillus niger*, requires a good supply of available zinc for optimum growth (Raulin, 1869; Bertrand and Javillier, 1911; Javillier, 1912; Gollmick, 1936). Recently the *A. niger* test has been used extensively for estimating the zinc-supplying power of soils (Gerretsen, 1948; Nicholas and Fielding, 1951; Donald *et al.*, 1952; Bould *et al.*, 1953a,b). Bould *et al.* found zinc deficiencies of apples and pears growing on soils containing less than 2 p.p.m. of zinc removable by *A. niger*, normal

soils contained about 10 p.p.m. Tucker *et al.* (1953) obtained 0.6 to 2.88 p.p.m. of zinc for Florida soils known to respond to zinc and from 1.6 to 21.5 p.p.m. in Illinois soils.

Tucker and Kurtz (1955) compared zinc removal from soils by *A. niger* and by soil extraction with 0.1 *N* HCl, acetic acid, EDTA, and dithizone solutions. The amount of zinc removed during a six-week extraction period by successive extractions with 0.1 *N* HCl and by *A. niger* were approximately equal. The removable zinc by these procedures constituted about one-fifth of the total. Very little zinc was found in the exchangeable and organic forms. The various availability tests removed about the same amounts of zinc. The authors considered the *A. niger*, dithizone, and 0.1 *N* HCl procedures most convenient and rapid. Since many zinc-deficient soils contain free limestone, 0.1 *N* HCl would not be widely applicable.

Although comparative studies have not been made on an extensive scale where zinc deficiencies occur, the *A. niger*, dithizone, and possibly the EDTA methods have shown value in differentiating zinc-deficient soils and merit further study.

XI. Control of Zinc Deficiency

Four general procedures for the control of zinc deficiency have been studied: (*1*) Management practices such as intercropping, green manure crops, and soil treatment with organic manures; (*2*) soil treatment with zinc-containing materials; (*3*) injecting zinc salts into plants or driving zinc-coated materials into trees; (*4*) application of zinc-containing sprays or dusts.

1. Management Practices

Several workers have reported that growing alfalfa has helped alleviate zinc deficiency symptoms in fruit trees or grapes (Haas, 1936; Chapman *et al.*, 1937; Reed, 1938; Ballard and Lindler, 1934). Hoagland *et al.* (1937) planted apricot and corn seedlings between alfalfa plants which had been planted a year previously in a zinc-deficient soil. No deficiency symptoms developed. Since the alfalfa roots were confined in pots, the alfalfa must have had a direct effect in increasing the availability of the soil zinc.

Chandler *et al.* (1934) reported that alfalfa will make satisfactory growth on a soil on which other plants show severe zinc deficiency symptoms. Millikan (1953) found that alfalfa grew much better than subterranean clover under conditions of zinc deficiency but that subterranean clover made the best growth with copper deficiency. Growing alfalfa and subterranean clover together did not change these results.

The beneficial effects of alfalfa on available zinc in soils no doubt result in part from the deep-feeding roots' contacting deep soil depths and bringing zinc to the surface. This effect also results in part from the ability of alfalfa to make vigorous growth on all but the most extremely zinc-deficient soils. There is also, however, evidence of a direct role of alfalfa in increasing the available zinc supply to plants growing in association with it. No direct explanation for this is apparent.

Rogers *et al.* (1939) attributed the beneficial effects of "land resting" on zinc deficiency to the uptake of zinc by vegetation and the release of this through decomposition. Weeds and grasses from plats rested 1 year averaged 70 p.p.m. of zinc, and those from plats rested two years averaged 140 p.p.m.

2. *Soil Treatments*

Mowry and Camp (1934) successfully cured bronzing of tung trees in Florida by soil treatment. They recommended application rates of 0.25 to 0.50 pound of zinc per tree for trees under eight years of age. The soil involved must have been extremely sandy and of low zinc-fixing capacity, for usually much larger applications have been required for trees. Chandler (1937) reported that in California soils of lowest zinc-fixing power, 1000 pounds of zinc sulfate per acre if spread uniformly over the soil surface will control nearly all zinc deficiency symptoms of trees for up to three years. Under the same conditions, 300 pounds were equally effective if kept within 2 feet of tree trunks. In some soils 2500 pounds of zinc sulfate per acre, all within 2 feet of tree trunks, were not fully effective.

Zinc sulfate treatments have given special benefit to peach trees suffering from arsenic injury. In Washington (Thompson and Batjer, 1948) maximum recovery occurred with a combination treatment of zinc sulfate and a high rate of a nitrogen fertilizer. These investigators recommend that zinc sulfate be applied once to soil near trunks of injured trees at a rate of 8 pounds per tree. The Alabama Agricultural Experiment Station (1942) also reported benefit to arsenic-injured peach trees from zinc sulfate applied either to the soil or sprayed on the foliage.

Zinc-deficient row crops have generally benefited from side-dressing treatments with zinc salts. Barnette (1937) reported control of white bud of corn by soil applications of 12 pounds or more of 89 per cent zinc sulfate. All soluble zinc salts were about equally effective. Metallic zinc was not noticeably helpful at 5 pounds per acre but was effective at 40 pounds. A broadcast application of 15 pounds of zinc sulfate on this soil resulted in earlier maturing oats than on soil not treated.

In recent field and greenhouse studies in California (Lingle and

Holmberg, 1956) foliage sprays were more efficient than soil applications for zinc-deficient sugar beets and sweet corn. Four pounds of zinc sulfate per acre applied as a foliage spray produced greater yields of sugar beets than 50 pounds side-dressed. Twenty-five pounds of zinc chelate side-dressed gave slightly higher beet yields than 50 pounds of zinc sulfate. Zinc chelate did not appear to be quite as effective as zinc sulfate when used as a spray.

A number of field and vegetable crops suffer from zinc deficiency on some soils brought under cultivation in the Columbia Basin. These have responded to both soil and spray treatments (Viets *et al.*, 1953, 1954a,b). Frequently, however, additional benefits were obtained from spray applications to plants that had been side-dressed with 23 pounds of zinc per acre as zinc sulfate. This indicates a consistently better response from spray than soil applications for at least the first year. Seven pounds of zinc sulfate per acre have been effective as soil treatments in benefiting several crops in sandy, zinc-deficient soils in South Australia (Riceman, 1949).

3. *Injections*

Many reports have indicated good recovery of trees if zinc salts are placed in holes bored at intervals around the trunks (Finch and Kinneson, 1933; Chandler, 1937; Chandler, 1942). In some instances holes bored in trunks or roots of trees have been attached to a reservoir of zinc sulfate solution. Chandler (1942) reports that injection treatments never fail if the trunk is sound and the deficiency is zinc. An injection treatment usually lasts two or three years before zinc deficiency symptoms are again evident.

Injection is not in general use because the procedure requires considerable hand labor and time, and streaks of sapwood are often killed for several feet above and a short distance below each injection site.

Trees will absorb zinc from zinc-coated nails or galvanized iron. Chandler (1942) recommends strips of 22 gauge galvanized iron $\frac{3}{4} \times 2$ inches driven into the trunks or branches of trees at frequent intervals. Again the labor is so great that the method is not used extensively.

4. *Spray Applications*

Control of zinc deficiencies in fruit trees has been extensively reported in the book edited by Childers (1954). The evidence cited is predominantly in favor of spray applications to foliage or to trees in the dormant state.

Deciduous trees such as apple, apricot, peach, pear, plum, and almond respond well to spraying with rather strong solutions of zinc sulfate during the dormant season before the buds have swelled much.

Solution concentrations recommended (Chandler, 1942; Childers, 1954) vary from 25 to 50 pounds of zinc sulfate per 100 gallons every other year. Application of 10 pounds per 100 gallons every year has also given good control. Some damage may occur to buds if swelling is advanced at the time of application of concentrated solutions, but usually the damage has not been of economic importance. Dormant zinc spray applications are often combined with bordeaux mixture on lime-sulfur to save labor. Brough (1950) states that if zinc deficiencies of deciduous trees are severe in Victoria spraying may be needed three or four consecutive years. Thereafter, spraying with zinc sulfate every second year was sufficient.

Zinc sprays applied to foliage are moderately dilute and are usually made alkaline by addition of lime or soda ash. Foliage sprays usually contain from 4 to 10 pounds of zinc sulfate and 7 or more pounds of hydrated lime or sodium carbonate per 100 gallons of water. Chandler (1942) recommends 6 pounds of zinc sulfate and 3 pounds of lime or soda for deciduous trees. A similar rate is recommended for citrus by Chapman *et al.* (1945). Lingle and Holmberg (1956) used 0.5 per cent zinc sulfate solutions for spraying field and vegetable crops. Best results are usually obtained by spraying while plants are still in the rapidly growing stage. Mature leaves usually do not respond satisfactorily.

Zinc deficiencies are extensive in grapes. Variable results have been obtained both from using foliage sprays and from spraying vines with more concentrated solutions during dormant periods. Investigations in California and Australia with grapes have shown best results from swabbing freshly pruned surfaces of spur-pruned vines with a solution of 1½ to 2 pounds of zinc sulfate per gallon of water. Spraying pruned grape vines with similar zinc sulfate solutions has given as good results in Australia as swabbing the freshly cut surfaces (cf. Christ and Ulrich, pp. 325–328, in Childers, 1954).

Hewitt and Gardner (1956) flushed canes of Thompson Seedless grapes with Zn^{65} sulfate solutions. The radiozinc was markedly fixed on the cane vessel walls. This fixed zinc could not be removed by distilled water but was readily displaced by nonradioactive zinc sulfate solutions. Zinc was absorbed more readily from solutions of high pH than from those of low pH.

Johnston (1946) applied various zinc preparations as dusts instead of sprays for the control of mottle leaf of citrus. Zinc sulfate gave best results, but zinc oxide and metallic zinc at 4 per cent in talc gave good control. Dusts have not been widely used in general field treatments.

Spray applications are also frequently used for row crops. Lingle and Holmberg (1956) obtained better yield increases from spray applications of zinc sulfate (4 pounds) in 100 gallons of water than from 50

pounds of zinc sulfate side-dressed. Viets *et al.* (1954b) often obtained additional benefits with row crops from foliage applications after the crops had been side-dressed with zinc sulfate.

5. *Chelates*

Chelates have attracted considerable attention as means for holding heavy metals in a soluble, available state for plants, but by far the most extensive use has been with iron. Although a number of chelating compounds are being used for iron, available data for zinc are restricted to zinc complexed with ethylenediamine-tetraacetate (EDTA). The stability constant for zinc EDTA is 16, whereas that for ferric iron is 25.1. Thus, if EDTA were added to a solution containing equal amounts of Zn^{++} and Fe^{+++} ions the EDTA would react with one billion times more iron than zinc. Under these conditions zinc chelates would not be effective in the presence of ferric ions. However, under alkaline conditions iron is precipitated more strongly than zinc, and consequently it has been proposed that zinc EDTA may have practical value under alkaline conditions (Stewart and Leonard, Chapter 16, Childers, 1954).

Butler and Bray (1956) applied zinc EDTA and sodium EDTA to Muscatine silt loam and to Oquawka fine sand, each at pH 5.0, and grew perennial ryegrass. The treatment rates provided up to 5.0 p.p.m. of zinc as Zn EDTA and comparable amounts of sodium EDTA. Zinc EDTA treatments did not increase the zinc content of the ryegrass on the silt loam soil, but there was a large increase on the fine sand soils. Sodium EDTA treatments did not alter the zinc contents of the plants. The zinc added as EDTA to the silt loam soil disappeared from both the water-soluble and exchangeable forms, but there was some build-up of exchangeable zinc in the sand.

Alben (1956) made zinc EDTA treatments to the soil around rosetted pecan trees in Texas and Louisiana. Best results were obtained on Ruston and Norfolk sandy loam soils of pH 5.4 to 6.4. Treatments made in the spring of 1953 did not completely control rosetting, but the next year rosetting did not occur on trees that had received either the 1 or 2 pound treatments. These soils required 20 to 30 pounds of zinc sulfate per tree for rosette correction. Less response was obtained from zinc EDTA on acid soils as the content of clay and silt increased. Little or no response was obtained from the zinc chelate treatment on Yahola soil of pH 6.4 to 7.4.

Lingle and Holmberg (1956) compared zinc EDTA with zinc sulfate for treating zinc-deficient sugar beets both as soil treatments and as spray. Zinc sulfate sprays resulted in yields of 34 tons per acre; zinc EDTA sprayed plants yielded 32.7 tons; zinc sulfate (50 pounds per acre) added to the soil gave an average yield of 22.1 tons; and

zinc EDTA at 25 pounds per acre added to the soil gave a yield of 28.6 tons. A difference of about 6.6 tons was required for significance. Thus, whereas the zinc EDTA was superior to zinc sulfate for soil treatment, the recommended treatment in view of costs was the zinc sulfate spray.

Results to date indicate that zinc EDTA has not given satisfactory results for zinc deficiency control through soil treatments except possibly on acid sandy soils of low zinc-fixing capacity. Also, since zinc sulfate sprays are inexpensive and generally satisfactory, there does not seem to be the serious need for zinc chelates that exists for iron chelates.

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DEFOLIATION AND DESICCATION: HARVEST-AID PRACTICES

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I. Introduction

1. General

Defoliation and desiccation have been practiced for many years. Hand defoliation is used on hops and nursery stock; desiccation is the principal effect obtained in the curing of hay, swathing of grains, and shocking of corn. Chemical defoliation and desiccation have been recently discovered to be valuable aids in the harvest of crops. In 1955 approximately 2,968,973 acres of cotton were treated with defoliants and desiccants (Tharp, 1956). This review discusses such harvest-aid practices and the basic factors which underlie these practices. Previous reviews have been brief, with limited coverage of the literature (Hall, 1957; MacDonald, 1952; Stahler, 1953).

2. Definitions

Abscission: the process by which a leaf or other part is separated from the plant. (In its full sense, abscission includes the splitting of fruits and similar types of separation.)

Abscission zone: a region of the plant, usually well demarked, in which abscission occurs. The leaf abscission zone lies at the juncture of leaf and stem.

Cut-out: a stage in the development of some plants characterized by absence of both vegetative growth and flowering. When it occurs in cotton, it is usually reached relatively late in the life cycle.

Defoliant: a chemical which induces defoliation; in the full sense, any agent which induces defoliation.

Defoliation: accelerated leaf abscission.

Desiccant: a chemical which induces desiccation.

Desiccation: accelerated drying of plant or plant part. (In the rest of this review the term will mean chemically induced desiccation.)

Second growth: a resumption of growth after cut-out or defoliation, resulting in the production of new leaves.

Plant hormones and other regulators: See Van Overbeek *et al.* (1954) for the usage recommended by a Committee of the American Society of Plant Physiologists, which is followed here.

II. Defoliation: Basic Aspects

An introduction to the subject of defoliation is included in "Abscission and Plant Regulators" (Addicott, 1954), and some aspects of leaf

fall are discussed in a popular article on work with *Coleus* (Jacobs, 1955a). Comprehensive treatment of the basic factors and the theoretical aspects of the physiology of abscission is given in a recent review (Addicott and Lynch, 1955). This section therefore will discuss only the more general aspects of leaf abscission as they relate to defoliation of field crops.

1. Morphology

In the leaf base morphological changes precede and accompany the weakening which leads to leaf fall. Knowledge of these changes has aided the planning and interpreting of defoliation experiments.

The tip of the leaf matures first, its base last (Esau, 1953), and the tissues at the very base of the leaf never differentiate as fully as do the contiguous tissues of the petiole. The cells remain relatively small and compact and their walls thin, often lacking lignin and suberin. This region of arrested development is the leaf abscission zone. As the leaf becomes senescent, part of this basal region resumes development (Fig. 1). Typically, cell divisions occur in a plate one or more cells thick, extending across the abscission zone. Usually, the divisions occur within existing cell walls so that little or no enlargement of the zone occurs. Actual separation of the leaf follows the dissolution of parts of these cells. The cells which directly participate in dissolution form the separation layer. In some cases, dissolution involves only the pectic middle lamella lying between two tiers of cells; in other cases, both celluloses and pectic substances dissolve and the entire cell wall disappears; in a few cases (e.g., certain *Rubus* species), a layer several cells thick dissolves (H. W. B. Barlow, unpublished; Addicott, 1954). In cotton, cell division begins at the lower edge of the abscission zone and progresses upward, and is followed by dissolution (V. H. Ramsdell, V. L. Hall, and K. C. Baker, unpublished). In leaflet abscission of beans, these processes begin in the center of the leaflet abscission zone and progress to the periphery (Brown and Addicott, 1950). Actual separation of the leaf may be aided by internal mechanical factors such as tensions (Livingston, 1948) and of course by external factors such as wind.

The above descriptions cover typical morphological changes accompanying abscission. Some of the more important variations from this pattern follow. In deciduous trees, cell divisions commence earlier and continue longer, resulting in a well-defined layer several cells thick (Eames and MacDaniels, 1947). In some plants (e.g., *Impatiens*) and under some conditions (e.g., exposure to ethylene) no cell divisions precede cell wall dissolution. In other plants (e.g., tobacco, potatoes, and most cereals) dissolution does not occur, senescent leaves wither-

ing in place on the plant; in such cases any separation of leaves from the plant is the result of action by external agents.

Because cell divisions are commonly associated with abscission it is frequently assumed that they are essential to abscission, that separation could not be accomplished without them. But there are numerous

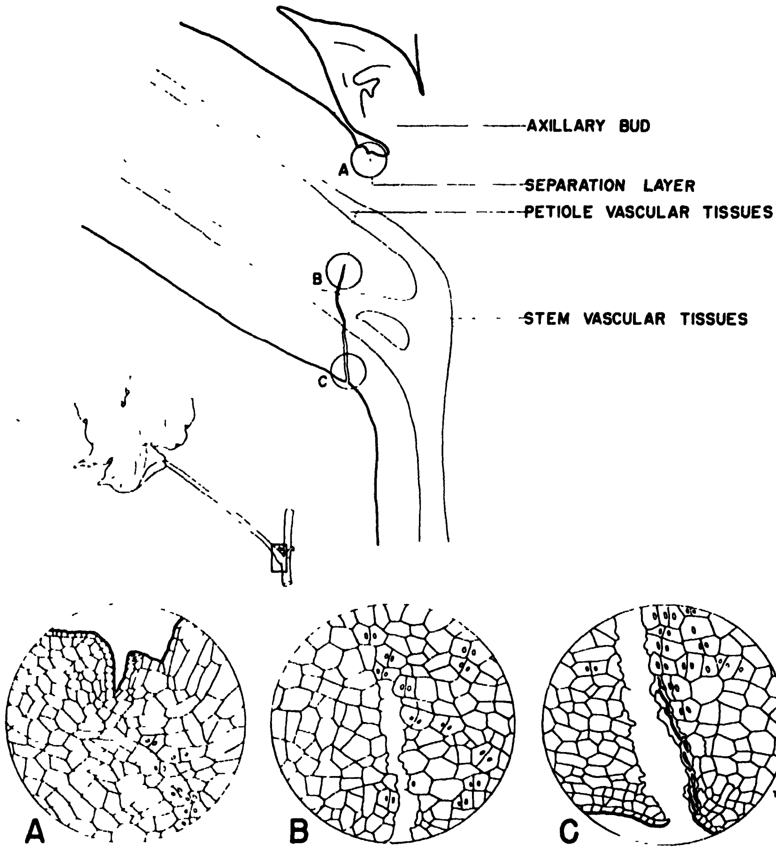

Fig. 1. Diagram of the leaf base of cotton. Circles *A–C* correspond with the camera lucida drawings below, which show relationship of cell divisions to separation layer. Separation occurs between dividing cells on the distal side of the abscission zone. Cell divisions, followed by separation, commence at the lower edge of the abscission zone and progress upward. (By Katharine C. Baker.)

cases in which separation does occur without prior cell division, and Gawadi and Avery (1950) suggest that the function of cell divisions, where they occur, is the production of the protective scar tissue over the area exposed by abscission, and that the cell divisions are not essential to abscission. Evidence from other types of abscission, especially flower

abscission and dehiscence, provide support for this view (Addicott and Lynch, 1955).

The essential phase of leaf abscission is the dissolution of cell walls; typically this dissolution so weakens the separation layer that the weight of the leaf effects the leaf fall. The recognition of the essential part played by cell wall dissolution has stimulated physiological research on factors, direct and indirect, which may influence it, and has stimulated a renewal of biochemical research on the hydrolysis of cell wall constituents.

2. *Physiology*

a. Leaf Abscission. Speculation and research in the physiology of leaf abscission goes back at least a hundred years and has brought knowledge of a wide variety of factors affecting abscission.

A healthy leaf remains attached to the plant indefinitely; it does not abscise unless it becomes unhealthy or senescent. To induce abscission, external factors must first induce such conditions. This, with other strong evidence, indicates that the leaf is an important if not the principal agent in the regulation of its abscission (Addicott and Lynch, 1955).

The hormone, auxin, retards abscission. This was first shown by Laibach (1933), whose application of orchid pollinia (rich in auxin) to debladed petioles retarded their abscission by several days. This retardation has been repeatedly confirmed for a variety of synthetic auxins through their application to debladed petioles (LaRue, 1936; Gardner and Cooper, 1943), to excised leaf abscission zones (Livingston, 1950), to intact leaves (Milbrath and Hartman, 1940), and to flowers (Wittwer, 1954; Wester and Marth, 1950) and fruits (Gardner *et al.*, 1939; Batjer, 1954).

Investigation has also shown a decrease of endogenous auxin with age of leaf (Avery, 1935). Shoji *et al.* (1951) found blade auxin of the young bean leaf to be high, of the expanding leaf to fall rapidly, of the fully mature leaf to remain at a low level, and of the senescent leaf with preabscission color changes to fall still lower, down to the level characteristic of the mature leaf stalk. In beans, the blade abscises from the leaf stalk, and Shoji's experiments demonstrated a rapid lowering of the auxin gradient across the blade abscission zone immediately preceding abscission. This suggested that lowering of the auxin gradient across the leaf abscission zone is an important factor in the initiation of abscission. A similar change in the auxin gradient across the leaf abscission zone of cotton was reported by H. R. Carns (unpublished) and confirmed by J. B. Storey (unpublished). And in *Coleus,* Jacobs (1955b) found the abscission of debladed petioles accelerated by auxin moving basipetally from leaves in the apical bud.

Evidence in support of auxin gradient regulation was also obtained from experiments with applied auxin. Application of IAA (indoleacetic acid) to the distal (blade) side of excised abscission zones of bean leaves was found to retard abscission, whereas application to the proximal (petiole) side of the abscission zone was found to accelerate abscission (Addicott and Lynch, 1951). These observations have been confirmed by D. S. Louie (unpublished). Certain experiments reported by Gaur and Leopold (1955) also support this concept, although others led them to conclude that abscission was controlled by the quantity of applied auxin rather than by the gradient of auxin. Unfortunately the techniques of these experiments were not described fully enough to permit evaluation of the results.

If auxin is applied to the entire plant or to most of its leaves, abscission is usually retarded. The few exceptions are difficult to evaluate, for many factors, including absorption, translocation, and inactivation, may affect the response of a particular plant to a particular application. In debladed *Coleus* petioles, Gaur and Leopold found that applications of NAA (naphthaleneacetic acid) in lanolin at concentrations higher than 1.0 p.p.m. retarded abscission but at concentrations lower than 1.0 p.p.m. accelerated abscission. None of the numerous previous workers reported this acceleration effect, but none used NAA in such low concentrations. It is probable that this effect was peculiar to NAA; this compound differs considerably in its physiological properties from IAA, the most common endogenous auxin. For example, NAA functions as an anti-auxin in its effects on the flowering of pineapple (Gowing, 1956a, b).

An abscission-accelerating substance has been obtained from senescent leaves of beans and other plants by Osborne (1955); this finding has been confirmed by Biggs and Leopold (1956). This substance not only accelerates abscission when applied alone but when applied with IAA counteracts the abscission retardation effect of the IAA. A somewhat similar effect is produced by the fungus *Omphalia*, which infects coffee leaves and accelerates their abscission apparently by an enzymatic inactivation of the auxin of the leaf (Sequeira and Steeves, 1954).

Investigation of the respiratory phases of abscission has disclosed several important facts (Carns, 1951). In excised abscission zones of beans, respiration was found essential to abscission; in the absence of oxygen or in the presence of any of several inhibitors of respiratory enzymes, abscission did not occur. Evidence of a climacteric rise in rate of respiration during abscission was found, suggesting, as does the morphological evidence, that the process of abscission is closely similar to the process of ripening in fruit. An especially interesting discovery

was that oxygen at concentrations higher than 20 per cent accelerated abscission, and at concentrations higher than 40 per cent accelerated it to the maximum rate, i.e., a rate as rapid as with any accelerant yet tested. Carbon dioxide was found by Yamaguchi (1954) to retard abscission in excised leaf abscission zones of beans.

The carbohydrate metabolism of the plant also affects abscission. A low carbohydrate economy leads to early abscission. Conditions which lead to carbohydrate accumulation tend to delay abscission.

Many environmental conditions affect abscission. Temperature affects it, as temperature affects most physiological processes. In beans the rate of leaf abscission is maximal at temperatures between 25° and 30° C.; on both sides of this temperature range the rate falls. But short exposure to extreme temperatures, either high or low, accelerates abscission, apparently by injuring the leaf tissue. Ice crystals in the abscission zone have been alleged to facilitate abscission in deciduous trees, but present evidence does not support this view (Eames and MacDaniels, 1947). Water deficiency may be followed by leaf abscission, especially when the deficiency develops rapidly. A shortening photoperiod is correlated with autumnal leaf abscission and can be its initiating factor (Olmstead, 1951); Olmstead's experiments indicated that the effects of photoperiod on abscission are indirect, probably through effects on hormones.

Mineral nutrition affects leaf abscission. When essential minerals are ample, leaves are retained longer than when essential minerals are deficient; deficiencies of nitrogen, calcium, zinc, sulfur, and magnesium lead to premature leaf abscission (Addicott and Lynch, 1955). Deficiencies of nitrogen and zinc are correlated with a reduction in auxin (Avery *et al.*, 1937; Skoog, 1940); how deficiencies of the others bring about abscission is not known.

Leaf abscission may be retarded or accelerated by application of a number of chemicals. Most of these will be considered in the section on defoliation, below. Retardants are NAA, 2,4-D (2,4-dichlorophenoxyacetic acid), 2,4,5-T (2,4,5-trichlorophenoxyacetic acid), and many related compounds. Since these compounds are either auxins in the strict sense or are structurally closely related to auxins, it is generally believed that they retard abscission by augmenting endogenous auxin. Accelerants include ethylene, acetylene, and related compounds (Crocker, 1948), oxygen (discussed above), and defoliants (discussed in Section II, 2, b). Because ethylene is produced by certain fruits and leaves, Gawadi and Avery (1950) suggested that it is an endogenous regulator of abscission with an action opposite to that of auxin. But consideration of recent evidence indicates that ethylene is probably not an endogenous regulator of abscission (Addicott and Lynch, 1955)—

a conclusion which has also been reached for *Coleus* by Jacobs (1955b). However, where conditions permit its use, ethylene is a very effective abscission accelerant and a useful defoliant (see Section III, 3).

In hope of finding clues to the processes underlying abscission, studies have been made of the leaf changes preceding leaf abscission (Hall and Lane, 1952). Such changes include development of anthocyanin; disappearance of chlorophyll (Wolf, 1956); exit of nitrogen, phosphorus, potassium, iron, magnesium, and possibly zinc and copper (Williams, 1955); increased susceptibility to leaching of mineral nutrients; disappearance or change in form of carbohydrates; and the auxin changes described above. With the exception of the last, these changes appear to be side effects, not directly related to the process of abscission.

An understanding of the regulation of abscission is made difficult by the paucity of our knowledge of the physiological action of the factors affecting abscission. At present, auxin appears to be the principal endogenous regulator of abscission, the auxin gradient across the abscission zone determining the onset and the rate of abscission (Addicott *et al.*, 1955a). (For a more detailed discussion of this and older theories of abscission regulation, see Addicott and Lynch, 1955.) Of the factors other than auxin, many appear to act through their effects on auxin, e.g., nitrogen deficiency, which reduces the amount of auxin in the leaf. Other factors may act by predisposing the cells of the abscission zone, or by directly promoting cell wall dissolution; such effects, however, have not so far been found.

b. Defoliation. Defoliant application produces approximately the same effect as mechanical deblading: an acceleration of abscission. To be effective, a defoliant application must be followed by substantial injury to the leaf blade without much injury to the abscission zone. If the abscission zone is severely injured its cells will not function.

Swets and Addicott (1955) applied a defoliant to the upper surface of the blade of beans and to the lower surface and found no difference in the subsequent leaf fall; they also applied a defoliant to the upper surface of the mid-vein alone and to the entire upper surface and found no difference in subsequent leaf fall. In cotton, Addicott and Walhood (1955) found that application of defoliant to both blade and petiole produced more rapid defoliation than application to blade alone, the petiole showing some ability to retard abscission, although much less than the blade. In excised cotton abscission zones, direct application of a series of representative defoliants failed to accelerate abscission (Addicott *et al.*, 1955b); in every case the defoliant at low concentrations was without effect and at high concentrations retarded abscission. Altogether this evidence indicates that defoliants act mainly

on the blade, to a lesser degree on the petiole, and do not act directly on the abscission zone.

This conclusion as to the parts of the plant which must be injured to produce satisfactory defoliation is not matched by any conclusion as to the necessary type of injury. In cotton each defoliant produces its own pattern of injury, distinctive in degree of injury, pigment change, speed of desiccation, and portions of blade affected (Johnson, 1955). Calcium cyanamide produces a very mild blade injury with slight loss of chlorophyll, often an increase in anthocyanin, and usually a slow loss of blade moisture. Sodium chlorate produces relatively greater blade injury with more or less complete disappearance of chlorophyll and other pigments, and loss of blade moisture. Other defoliants produce an injury mainly of the leaf veins, still others, of the mesophyll. Degree of injury also varies with defoliant concentration, environmental conditions, and variety of cotton.

Other changes induced by defoliants include hydrolysis of carbohydrate and nitrogenous materials (Hall and Lane, 1952), increased respiration (R. O. Thomas, unpublished; Hall and Lane, 1952), decreased auxin (Swets and Addicott, 1955), and probably production of ethylene (Jackson, 1952).

The chemical structure of defoliants gives little help toward understanding the physiology of defoliation; it would be difficult to imagine a greater variety of chemicals with a common biological effect. At the present time, calcium cyanamide and sodium chlorate are the most widely used defoliants. Other chemicals offered for sale within the past five years include ammonium thiocyanate, sodium monochloroacetate, sodium ethyl xanthate, sodium dichromate, aminotriazole, butynediol, and 3,6-endoxohexahydrophthalate. Still other chemicals known to have defoliant properties show even greater structural variety. Among these are zinc chloride, sodium hypochlorite, thiourea, various petroleum fractions, octynediol and its related compounds, phenyl mercuric salts, and tripropyl phosphotrithioite.

This variety of chemical structure and variety of injury produced make highly improbable any chemical specificity of defoliant action. That is, it is improbable that defoliants act by directly affecting a specific physiological or biochemical mechanism. The one action which defoliants do have in common is leaf injury within a fairly well-defined range of degree. A slight injury is ineffective; and a severe injury kills the cells of the abscission zone, preventing abscission; an effective degree of leaf injury sets in motion a chain of events leading to cell wall dissolution in the separation layer and ultimate separation of leaf from plant. Which of the known physiological effects of defoliants are part of the essential chain of reactions leading to abscission and which are

unimportant side effects is still largely a matter of conjecture. It is probable that reduction of auxin is an essential reaction; and present evidence suggests that increased respiration is also essential. The action of ethylene has been suggested as a necessary intermediate step in defoliation (Hall and Lane, 1952), but there is little supporting evidence for this suggestion.

Defoliant applications do not always produce the expected degree of defoliation. Such unsatisfactory defoliation is not yet understood, but several contributing factors are recognized. One factor is failure of the defoliant to enter the leaf. This failure is often associated with too little moisture on or in the leaf. Some defoliants have been unsuccessfully applied in fine droplets under conditions of very low humidity and presumably were in a dry crystalline state before reaching the plants, making penetration of the leaf difficult or impossible. Calcium cyanamide applied as a dust does not produce defoliation unless there is sufficient moisture on the leaf surface to hydrolyze the defoliant. (Other difficulties of application are discussed in Section III, 2.) Another factor leading to unsatisfactory defoliation is variation in range of successful defoliant concentrations; some defoliants act only within a relatively narrow range of concentrations, e.g., endothal (W. R. Mullison, unpublished), whereas others act over a very wide range of concentrations, e.g., calcium cyanamide. A further factor is variation in response of plant varieties to defoliants; at Shafter, California, not only are certain cotton varieties from the eastern United States ready for defoliation weeks earlier than the western variety (Acala) but they require considerably less defoliant. And every variety differs from field to field and from season to season, so that concentrations effective at one time or place are not always effective at another time or place. Reaching the plants as a dust or spray, defoliants cover only a small fraction of the leaf surface; many unsuccessful defoliants produce correspondingly small scattered spots of leaf injury. But successful defoliants produce a general injury, apparently as a result of their ability to move throughout the leaf. Some defoliants can move through the stem from one leaf to another (Swets and Addicott, 1955), but such movement does not appear to occur to any significant extent in commercial defoliation.

III. Defoliation: Practice

1. Cotton: General Factors

Cotton defoliation practice originated in the accidental drift of calcium cyanamide to a field of cotton The cotton was wet with dew and the resulting defoliation attracted considerable attention. Subsequent

experiments disclosed that calcium cyanamide dust applied during periods of dew was a very satisfactory defoliant (E. E. Hall and Harrell, 1942).

Interest in cotton defoliation developed rapidly, and in 1947 the Annual Cotton Defoliation Conferences were started. Originally the Conferences were sponsored by chemical firms; now they are sponsored by the National Cotton Council as part of the Annual Cotton Production Conferences. These conferences serve to bring together state and federal workers for exchange of information and planning of research. Basic contributions reported at the Defoliation Conferences are published in scientific journals. Information of value to the farmer is published annually by the National Cotton Council of America (Tharp, 1953). These publications have formed the basis of a series of bulletins distributed by the Extension Services of a number of states. These bulletins and other information of local importance are available through the County Agricultural Agents in cotton-growing regions. The following discussion is based on the above materials, particularly on Harrison *et al.* (1956), and is limited to experience in the United States.

a. Advantages of Defoliation. Defoliation is advantageous in the hand harvesting of cotton and is especially advantageous in its machine harvesting. Defoliation helps lodged plants to return to an erect position. It removes the leaves which can clog the spindles of the picking machine, add trash, or stain the fiber. It accelerates the opening of mature bolls, and reduces boll rot. Defoliation reduces populations of insects which feed on leaves in late season. This has the immediate effect of eliminating fiber damage by the honeydew of aphids and white flies, and the more important long-range effect of greatly reducing the number of overwintering insects, such as the pink bollworm.

b. Limitations of Defoliation. Only mature leaves can be successfully removed; actively growing leaves are practically impossible to remove, and when present will stain the fiber during machine picking. Therefore it is advantageous to have plants in cut-out at the time of defoliation and to harvest as soon after defoliation as practicable, especially when conditions favor second growth.

Defoliation should not be attempted where the growing season is so short that the cotton plant needs every day prior to frost to produce maximum quality as well as maximum yield (e.g., New Mexico and sometimes the northern San Joaquin Valley of California). Full development of fiber requires 35 to 40 days from flowering (Walhood, 1954). Development of fiber and seed ceases when a defoliant is applied to a plant; immature bolls will not develop further. Their seed will be lightweight and low in germination percentage, their fiber high in sugar and sticky—a source of trouble in spinning.

c. Economics. For a few years it was assumed that all cotton should be defoliated, but experience has shown that defoliation is not always profitable. Factors affecting the value of defoliation vary from farm to farm and often from field to field within a farm. Factors which should be considered in addition to those outlined in the preceding sections include the weed population, the variety of cotton, the probable market price, and the relative costs of machine and hand harvesting.

A three-year study of economic aspects of defoliation in Mississippi has recently been completed (Crowe and Carns, 1955). This study is by far the most extensive yet conducted; it considered such factors as plant height, foliage density, cultural practices, weather, natural leaf fall, second growth, weed population, boll rot, quality of fiber and seed, and market price as well as cost of defoliant application. It did not consider the value of insect control and a few other factors. Estimated net returns from defoliation ranged from a profit of $3.21 to a loss of more than $23.00 per acre. High losses occurred when premature defoliation reduced yield. The investigators concluded: " . . . conditions exist under which marked economic returns will accrue from the practice of defoliation. Such conditions are characterized by rank growth, heavily fruited cotton maturing in the presence of adequate moisture. By the same token, conditions frequently exist under which no such economic return can be expected. These are characterized by small, drought stressed, heavily fruited plants from which a large percentage of the leaves have fallen due to natural causes."

The complex of factors affecting defoliation necessitates an individual economic decision for each farm, for each set of conditions.

d. Defoliants. At present the most widely used defoliants are calcium cyanamide and various chlorates. Others either have received little acceptance or have not yet been fully tested.

Calcium cyanamide is currently the most popular single defoliant. It is sold as a fine black dust, 57 per cent calcium cyanamide. Its use requires moisture on the leaf surface; the calcium cyanamide itself cannot be absorbed but must be hydrolyzed into "free cyanamide" which can be absorbed (T. R. Cox, unpublished). Calcium cyanamide has produced satisfactory defoliation with application rates ranging from 5 to 150 pounds per acre. Typically, it produces a very mild injury, the leaves often falling while their moisture content is still high. Its use requires few precautions, although the dust is caustic and irritating to the throat and lungs of some persons.

Chlorate defoliants are usually sold in the form of dry crystals, to be dissolved in water and applied as a spray. Liquid preparations are also sold, and there is at least one formulation for application as a dust. Chlorates do not require a moist leaf surface. They produce moderate to

severe leaf injury and the blade is usually dry by the time the leaf falls. But although it is apparently safe to handle magnesium chlorate, the more popular sodium chlorate is a hazardous material, forming explosive compounds with organic substances. It should never be handled by untrained persons. For commercial use, sodium chlorate is mixed with various fire suppressors, usually sodium borates or magnesium chloride; these mixtures have proved quite safe.

During the last 10 years ammonium thiocyanate, butynediol, potassium cyanate, sodium acid cyanamide, sodium dichromate, sodium ethyl xanthate, and sodium monochloroacetate have been offered, but they are no longer on the market and appear to have no further commercial possibilities as defoliants.

Endothal (sodium 3,6-endoxohexahydrophthalate) first appeared on the market in 1951 and attracted considerable attention because of the very low rate at which it will defoliate (about 1 pound per acre). But because endothal defoliates within such a narrow range of rates its results have frequently been unsatisfactory.

Aminotriazole has been recently offered as a defoliant for use by itself or mixed with other defoliants. Its present cost, however, practically prohibits its use in either way. For example, a formulation of 1 pound of aminotriazole plus 5 pounds of sodium chlorate has given as effective defoliation as 10 pounds of sodium chlorate alone per acre, but the cost of the 6 pounds of mixture is considerably higher than that of the 10 pounds of sodium chlorate. Aminotriazole has, however, the important property of retarding second growth. Following the application of defoliants, including aminotriazole, axillary buds break and start to enlarge; but following aminotriazole the new leaves are extremely chlorotic and for two to three weeks their growth is very slow. Only after three or four weeks do the plants recover and resume normal leaf growth. This retarding property provides a useful though expensive tool for the temporary control of second growth. Although a number of physiological effects of aminotriazole are known (W. C. Hall *et al.*, 1954), how it retards second growth is far from understood. It appears to affect chloroplast metabolism rather than specifically inhibiting chlorophyll synthesis (H. Pyfrom and D. Appleman, unpublished).

Tributyl phosphotrithioite is an experimental defoliant which was tested widely in 1956 with such promising results that it will probably be offered for sale in 1957. With application rates of 2 to 4 pounds per acre it has removed almost all the top leaves in addition to the lower leaves. Also, the falling leaves did not catch on branches and bolls but fell directly to the ground, being still quite moist. This considerably reduced the picking trash.

e. Wetting Agents. Wetting agents (also called surfactants, spreaders, detergents, additives, activators) have been extensively tested for their ability to increase the effectiveness of defoliants, but results are inconclusive, probably owing to the chemical variety of wetting agents and to the complex factors involved in defoliation. Some companies recommend their use but others do not, and neither do the experiment stations. Much more work needs to be done following the lead of Currier's (1954) work on wetting agents and the penetration of herbicides.

f. Defoliability. Probably many physiological factors affect defoliability; a few are recognized and there is some evidence as to their roles. Leaf moisture and defoliability show a high correlation; the higher the leaf moisture, the more effective the defoliation (L. C. Brown, unpublished; D. S. Louie, unpublished). High leaf moisture of course favors the penetration of defoliants, but other effects may also be involved. Another factor is maturity; plants or parts of plants which are not mature defoliate poorly. A mature plant is characterized by foliage which has stopped growing and has become yellowish and/or reddish and has an average to heavy load of fruit. Cotton varieties differ considerably in the time required to reach maturity, and this difference largely accounts for varietal differences in defoliability. Other factors, including auxin relations, are suspected of influencing defoliability but research is lacking.

2. *Cotton: Agronomic Factors*

For fully satisfactory defoliation a field should have a uniform stand of erect plants with mature foliage. To bring a field of cotton to such uniformity requires careful work in the original planning of the field and throughout each growing season, carried out with particular attention to the following factors.

a. Soil. Soil should be uniform. Soil irregularities, such as patches of saline, alkaline, or sandy soil, produce irregularities of plant growth, followed by irregularities of defoliation and inefficient harvesting. Some soil irregularities can be avoided by careful grading of land to insure uniform water distribution and penetration. Irrigation (where applicable) and fertilization can often be regulated within a field to increase plant uniformity; they should be regulated to insure steady plant growth throughout the season. If growth stops prematurely, second growth and difficult defoliation usually follow.

b. Cultural Practices. A uniformly distributed plant population of 20,000 to 70,000 plants per acre is best for defoliation. For efficient application of chemicals as well as for harvesting, uniformity of plant size is also important. Rank growth which is apt to occur on field

borders or around "skips" defoliates poorly. Plants of excessive height should be topped. Done at the proper time, topping by hand or by special machine prevents lodging and insures erect rigid plants which can be easily penetrated by dusts or sprays. But if done too early, topping will stimulate excessive top branching, thus defeating its purpose. Excessive foliage and uneven boll loads are apt to follow insect attacks; weeds retard growth by taking water and nutrients from the cotton. Weeds also interfere with penetration of dusts and sprays and catch and hold fallen leaves, adding to harvest trash. Both insects and weeds should be controlled throughout the season.

c. Timing the Application of Defoliants. Determination of the best time for application is one of the most difficult problems confronting the farmer. To insure maximum yield and high fiber quality, application should be delayed until the youngest bolls are at least 40 days old. But if application is delayed too long, both temperature and soil moisture may fall, making defoliation increasingly difficult. The problem is further complicated by increasing fiber deterioration in the open bolls, changes in insect populations, etc. The farmer is faced with a dilemma; early application risks low yield and inferior quality, and late application risks poor response and fiber deterioration. Fortunately, when conditions indicate that defoliation will be profitable, it is usually possible to select an application time which will give maximum yield and quality as well as reasonably good response.

d. Bottom Defoliation. When cotton is rank, an early bottom defoliation is often desirable (Brown, 1953). Bottom defoliation reduces boll rot, accelerates the opening of lower bolls, and permits their earlier picking. It must be restricted to the lower parts of the plant, to parts with bolls at least 40 days old, or loss of fiber quality will result. Bottom defoliation tends to prevent lodging and kills or retards weeds, thus facilitating picking and later top defoliation.

e. Machinery. Defoliants are applied by airplane or ground machine. The principal problem in application is adequate coverage of foliage. In rank or lodged cotton, two applications may be necessary, the second after the fall of leaves injured by the first application.

Design of ground machines must insure that the defoliant reaches the plants when they are not compressed by the machine. To avoid injuring tall plants high-clearance ground machines must be used. Spraying should be done with fairly low pressure and gallonage, since relatively large droplets facilitate penetration of spray.

f. Culturally Induced Defoliation. In a few regions it is possible to induce defoliation by an adjustment of cultural practices. If water is withheld late in the season while the weather is still warm, considerable defoliation will result and remaining leaves will be too dry

and tough to stain fiber. But if done prematurely, this practice, like chemical defoliation, will reduce quality and yield. Other conditions, such as late insect attacks, may be followed by a defoliation sufficient for satisfactory machine picking.

3. *Other Plants, Including Ramie, Hops, Nursery Stock, and Stone Fruits*

Ramie is a perennial plant grown for the fiber in the stalk. In the United States it is defoliated with endothal and harvested three times a year. Application in the early morning at the rate of 0.3 pound per acre has given the most satisfactory results (A. P. Willis, unpublished).

In the culture of hops it has been customary to hand strip the leaves from the lowest 12 to 18 inches of the plant three times a season, at the same time removing the suckers. Tests in Oregon indicate that application of certain defoliants to the lower parts of the plant three times a season was as effective as this hand stripping and suckering and was considerably less costly (Keller and Laning, 1955). A reference to similar work done in England (Barnsley, 1953) was obtained too late to be used by the reviewers.

In the preparation of nursery stock for digging, shipping, or storage, defoliation has been used for many years; its principal advantages are the retardation of moisture loss and the prevention of diseases which start on the leaf. Defoliation has been accomplished by hand, by sheep, and by ethylene as well as by other means (Milbrath *et al.*, 1940). Hand defoliation is done in the field or by beating the stock after it is dug (Chandler, 1951; W. H. Chandler, unpublished). Sheep are regularly used in California for the defoliation of roses before digging (M. H. Kimball, unpublished). Ethylene is also used in the defoliation of roses; this requires a chamber with a constant high humidity and a 70° to 75° F. temperature. The optimum concentration of ethylene in the chamber is 10 p.p.m. obtained by releasing tank ethylene or by including a bushel of apples for every 400 to 500 cubic feet. This treatment does not accelerate the breaking of dormancy, but it does cause a greater number of buds to break in the spring, thus producing a more compact bush (Milbrath *et al.*, 1940).

Chemical defoliation of nursery stock still in the field has recently attracted considerable interest (Chadwick and Houston, 1948; Pridham and Hsu, 1954; Roberts, 1950; Zimmerman *et al.*, 1951). Pridham has found that field defoliation can be done with cotton defoliants, but they must be used with care or buds and young stems will be damaged. In his tests there was a tendency for defoliation to stimulate the breaking of dormant buds.

Interest has developed recently in defoliation as an aid in the control of bacterial canker of stone fruits. The bacterium invades the

plant through freshly exposed, incompletely healed leaf scars, and fresh paths of infection become available throughout a prolonged period in the fall when the leaves are shed. Repeated protective sprays of the trees over such a long period are not economical, and currently the trees are being defoliated in midautumn and then given a single application of a spray to protect them until the leaf scars are completely healed (W. H. English, unpublished).

IV. DESICCATION: BASIC AND GENERAL ASPECTS

1. *Introduction: Nature of Plant Response*

The value of desiccation was recognized some years ago when Murphy (1921) suggested its use with potatoes. Little work was done, however, until some 25 years later (Callbeck, 1949).

Where the principal purpose of desiccation is acceleration of the curing (drying) of the leaves and stems preceding threshing, the term spray-curing is descriptive and should be used (Jones, 1954). But to avoid confusion, the more general term desiccation will be used throughout this review.

In contrast to defoliation, where the abscission zone has an active role in leaf fall, in desiccation the role of plant tissues appears to be completely passive. The tissues contacted by the desiccant rapidly lose moisture and die, contiguous tissues die somewhat later, but remote tissues are unaffected. Usually all aerial parts, with the exception of seeds, are killed. The effect is similar to, if not identical with, that of contact herbicides. These chemicals together with their biochemical and physiological properties have been discussed in recent reviews (Blackman *et al.*, 1951; Crafts, 1953; Norman *et al.*, 1950).

The essential step in desiccation is cell membrane injury sufficiently severe to permit a rapid loss of water. The degree of injury to some extent determines the rate of desiccation, but environmental factors, especially relative humidity, are more influential. When the relative humidity is low, desiccation is rapid; when it is high, desiccation is slow. Between desiccants and defoliants there is no sharp line of demarcation. Their effects overlap; high application rates of defoliants may give considerable desiccation, low rates of desiccants may give considerable defoliation, especially when used on legumes. The individual chemicals, however, differ widely in effect; the defoliant calcium cyanamide rarely induces much desiccation except at very high rates and the desiccant pentachlorophenol rarely induces any defoliation, whereas sodium chlorate induces either defoliation or desiccation, depending on its rate of application. The basic difference between de-

foliants and desiccants lies in the degree and the extent of the injury produced.

The kind of plant partly determines whether an application is followed by defoliation or by desiccation. Some plants, such as the grains, are unable to abscise their leaves under any circumstances, and others, including tomatoes and potatoes, normally abscise few or no leaves. The only response such plants show to preharvest chemicals is desiccation. In plants which normally abscise their leaves, the response, defoliation or desiccation, is determined not only by the type of chemical applied but also by the physiological condition of the plant (Section III, 1).

TABLE I

Potential Advantages and Disadvantages of Desiccation

(Only a few of the listed advantages will apply to any given crop and then perhaps only in certain regions or in certain years.)

Potential advantages	Potential disadvantages
Reduces or controls insects and disease	Reduces quality
Permits harvest scheduling	Reduces yield
Desiccates weeds interfering with harvest	May leave toxic residues
Facilitates and simplifies mechanical harvest	
Attracts hand harvesters	
Improves quality	
Reduces moisture in seed	
Increases yields	

2. *Potential Advantages and Disadvantages of Desiccation*

Desiccation, like defoliation, is not always profitable or desirable. With some crops it is a profitable and established practice; with other crops it appears to have no value; and with many crops its value is yet to be determined. The different conditions prevailing in different regions makes desiccation of a crop valuable in one region but unnecessary in another. Desiccation can enable the harvesting of a crop that was planted late, overwatered, or overfertilized, but such a crop may yield little profit. Combined with good cultural practices desiccation can be a useful and profitable tool, but it is no substitute for good practices. Table I summarizes the potential advantages and disadvantages of desiccation. Only a few of these will apply to any one crop.

3. *Desiccants*

Desiccants include a wide variety of chemical types; early desiccants included such simple compounds as copper sulfate and sulfuric acid; more recently such complex compounds as substituted phenols

and endothal (sodium 3,6-endoxohexahydrophthalate) have come into use. Desiccants now in common use are listed in Table II; none of the numerous other chemicals which have shown desiccant properties have been widely accepted. The phenols are oil-soluble and diluting oils have the advantage of rapid penetration of plant tissues; the other desiccants listed are water-soluble and so have the advantage of convenience of formulation. The differences between desiccants, in their properties as desiccants, are relatively few, but they do differ in effectiveness under different conditions and on different crops. For example, endothal is often more effective than other desiccants when the foliage is heavy and green and the weather cool.

TABLE II

Common Desiccants and Rates of Application

	Commercial product	
Desiccant	Concentration[1]	Acre rate of application[2]
Dinitrophenol	55%	1 3 pt.
Endothal	0.63 lb./gal.	4 9 qt.
Magnesium chlorate	5 lb./gal.	3 8 qt.
Pentachlorophenol	4 lb./gal.	1 2 gal.
Sodium arsenite	4 lb./gal. (as arsenic trioxide)	2 10 qt.
Sodium chlorate	40%	8 20 lb.

[1] Concentrations commonly sold; other concentrations can be obtained.
[2] Rates used on various crops under various conditions. For specific recommendations consult the local extension service or experiment station.

The problems in the use of desiccants are similar to those met in the use of defoliants, discussed in Section III, 1.

V. Desiccation: Practice

1. *Beans Including Soybeans*

The few tests which have been conducted suggest that desiccation of beans is of little value (R. W. Allard, unpublished; Shafer and Hunck, 1954; F. L. Smith, unpublished; Tang, 1955; Wiltse, 1956). Desiccation prior to windrowing can reduce by 2 to 4 days the period spent in windrows, but the danger of yield loss is great (F. L. Smith, unpublished). Desiccation prior to direct combining might also be satisfactory under some conditions; but if foliage is dense the desiccant does not reach the stems and they remain tough and cause considerable trouble (R. W. Allard, unpublished). This problem could be solved by a translocatable desiccant, but there appears little prospect of finding

such a chemical. Moreover, in many bean-growing regions, direct combining results in loss of yield and is considered impractical (F. L. Smith, unpublished).

In every test with soybeans, desiccation early enough to hasten maturity has reduced yields (H. W. Johnson, unpublished; Smith, 1955); there is, therefore, little present prospect of its regular use in soybean harvest. It may be of value in soybeans grown for seed (Barnes, 1945) or occasionally when the crop is very late in maturing or when there is heavy infestation of weeds. But careful selection of variety and good cultural practices can prevent such conditions.

2. *Castor Beans*

In regions with early frosts desiccation of castor beans appears unnecessary but in other regions it has considerable use; approximately half the acreage in California and Arizona is currently being desiccated (L. H. Zimmerman, unpublished). Desiccation facilitates harvest and permits earlier harvest, thus avoiding losses from shattering. For best results the plants should be mature, not actively growing; premature desiccation reduces yield (Horn, 1952).

It is also possible to defoliate castor beans; endothal appears to be a superior to other defoliants (L. H. Zimmerman, unpublished).

3. *Corn and Grain Sorghums*

Interest in the desiccation of grain crops rests mainly on the possibility that desiccation might so reduce grain moisture that grain could be safely stored without further treatment. Many tests, however, have yielded unsatisfactory results: desiccation has not lowered moisture content with sufficient consistency to justify its recommendation (Ham and Willard, 1954; L. G. Jones, unpublished; Shafer, 1954a, b; D. G. Smeltzer, unpublished). Efficient desiccation of these crops is hindered by the sheathing leaves which prevent the desiccant from reaching underlying parts; at best, only a portion of the plant is desiccated. Moreover there is little reduction of moisture in the pieces of stalk which often accompany threshed seed of the grain sorghums and produce heat during storage. Desiccation can facilitate threshing by reducing the green foliage and weeds; but it is not considered an adequate substitute for good cultural practices such as early planting and thorough weed control (J. P. Conrad, unpublished; D. G. Smeltzer, unpublished).

4. *Cotton*

Cotton desiccation is standard practice in the high plains of Texas and Oklahoma, where yields are relatively low and production costs

must be kept low. Most harvesting in these regions is done by mechanical "strippers"—a much less expensive method than hand or spindle machine harvesting. At harvest time there is usually very little moisture in the cotton and it responds poorly to defoliants, green leaves often remaining on the plants; farmers therefore prefer to desiccate and have thoroughly dry leaves, since strippers remove leaves and burs with the seed cotton. Cotton desiccation is subject to many of the limitations described for cotton defoliation (Section III, 1, b).

In regions where cotton is very rank or has considerable second growth, defoliation is usually unsuccessful, and desiccation must be used preceding spindle machine harvesting. Desiccation eliminates leaf-staining of fiber but it adds considerable trash to the cotton picked by the machines.

5. *Small Grains*

Rice desiccation is of interest, especially in California, Arkansas, and Texas. Tests have demonstrated a number of its advantages, including reduced seed moisture (Hinkle, 1953; Tullis, 1951; Williams, 1952), desiccation of weeds (Tullis, 1951), earlier harvest (D. C. Finfrock, unpublished), and possibly easier combine harvesting (Hinkle, 1953). Many disadvantages have also been found; mill yields have been reduced (Williams, 1952), an off-flavor has been imparted to the grain by pentachlorophenol, the endosperm has been discolored by dinitrophenol, and under certain weather conditions moisture has been held on the surface of the plants by chlorates (Williams, 1952; D. C. Finfrock, unpublished). Adequate desiccation requires favorable weather, especially low humidity, and with low humidity the grain in the field often dries as rapidly without desiccation as with it (D. C. Finfrock, unpublished). Stormy weather after desiccation but before harvest has lodged plots of desiccated rice, leaving check plots standing (Williams, 1952).

In Arkansas farmers are now using desiccants when wet weather is prevalent during the harvest season, or when rice is lodged or there are green weeds in the fields. When the weather is dry there is little use of desiccants (R. J. Smith, unpublished).

In California, rice grown for seed is regularly desiccated to bring the moisture content down to 16 per cent before harvest and small acreages of rice grown for milling are desiccated to permit earlier harvest (D. C. Finfrock, unpublished). But rice desiccation has not given sufficiently reliable or valuable results to justify official recommendation for its use.

Desiccation of other small grains, such as wheat, barley, and oats, apparently offers no economic advantage (Cooper, 1952; C. E. Suneson,

unpublished). Little published information on desiccation of these crops was found by the reviewers. Of interest, however, is a study of absorption of sodium arsenite by oats; following a heavy preplanting application to the soil (400 pounds per acre, as As_2O_3), less than 1 p.p.m. appeared in the grain of the oats. This is far below the level considered harmful in foods (Terman *et al.*, 1952).

6. Small-Seeded Legumes

Desiccation of small-seeded legumes (alfalfa, various clovers, birdsfoot trefoil, etc.) is an established practice and is often of great value. It permits curing of the plants as they stand in the field, making windrowing unnecessary and thus preventing losses from the pod shattering common in windrows; windrow pod shattering has caused loss of as much as 90 per cent of a crop (Jones, 1954). Thus desiccation makes possible more rapid and efficient harvest by direct combine. It increases the uniformity of a stand with regard to dryness of leaves and quality of seed. Desiccation is also valuable in regions of short season where rain is common during harvest and in fields late in maturing. On the other hand, windrowing is practical (and desiccation unnecessary) where high humidity prevents shattering (Baghott *et al.*, 1954; Corns, 1953; Hoffman and Sylwester, 1952; Jones, 1952; Jones *et al.*, 1953; Peterson *et al.*, 1953; Phillips, 1954; Wiggans *et al.*, 1956).

The potential disadvantages of desiccating small-seeded legumes can usually be avoided. As with defoliation, seed development ceases with application so that seed must be fully mature at the time of application. Two applications may be required if the stand is not open and erect. To avoid losses from shattering, there must be close coordination of application with harvesting. For example, when the temperature is below 90° F., 1 or 2 days may be allowed to intervene between desiccation of birdsfoot trefoil and its harvest; but if the temperature is over 100° F., desiccation and harvesting should be done the same day (Peterson *et al.*, 1953). During the first days of storage, precautions against heating may also be necessary, as seeds from a desiccated crop usually have a higher moisture content than seeds from a windrowed crop. Straw from a desiccated crop may contain toxic residues and be unfit for live stock.

7. Potatoes

Desiccation of potato vines has been studied widely in the United States (Cunningham *et al.*, 1951; Houghland, 1952; Hoyman, 1952; Kunkel *et al.*, 1952; MacLachland and Richardson, 1951; Rich, 1950; Skogley, 1953; Werner and Dutt, 1941) and in a number of other

countries including Canada (Callbeck, 1949), France (Munster, 1950), Germany (Knoefel and Viertmann, 1954), Holland (Zaag, 1954), New Zealand (Allen, 1954), and Scotland (Boyd, 1952).

The following advantages of desiccation have been described: it prevents infection by late blight, prevents spread of virus diseases, reduces number of oversize and knobby tubers, speeds skin maturity, facilitates harvest, and permits timing of harvest (Houghland, 1952).

The relative merits of desiccation, rotobeating, and mechanical vine pulling have not been fully determined; the three methods are to some extent interchangeable. In some regions a combination of desiccation followed by rotobeating is preferred (C. E. Cunningham, unpublished; H. Findlen, unpublished; W. G. Hoyman, unpublished).

Desiccation is not often used in the Far West; it is considered best to leave the vines intact to shade the soil, protecting the tubers from heat injury (J. C. Bishop, unpublished). It is not used in some regions where frost, withholding of irrigation water, or rotobeaters do a satisfactory job of vine killing (J. C. Bishop, unpublished; J. G. McLean, unpublished; H. O. Werner, unpublished).

8. *Tomatoes*

In California, considerable interest has developed in recent years in desiccation of tomatoes (T. Lyons, unpublished). The principal advantages are the attraction of hand harvesters, the facilitation of machine harvesting, and the speeding of both hand and machine harvesting. The desiccant commonly used is sodium chlorate and there is no indication that it damages ripe fruit; but premature desiccation reduces yield.

9. *Miscellaneous Crops, Including Table Beets, Grasses, Flax, Safflower, and Sunflower*

Desiccation of table beets grown for seed would greatly facilitate mechanical harvest, especially if it could dry the main stalk. One recent test with dinitrophenol satisfactorily dried the foliage but failed to dry the main stalk. In this test the seeds were unaffected, but there was enough toxic residue in the fruit hull seriously to reduce germination (J. F. Harrington, unpublished). It is possible that a desiccant can be found which will not affect germination.

With grasses grown for seed the principal advantage of desiccation is facilitation of mechanical harvest (Shafer, 1954c; L. G. Jones, unpublished; E. P. Sylwester, unpublished). Undesirable effects have been observed in at least one case; both germination and seedling vigor were reduced in tall fescue following application of dinitrophenol (L. G. Jones, unpublished).

Flax, safflower, and sunflower are occasionally desiccated in California (P. F. Knowles, unpublished). Flax desiccation, primarily for preharvest weed control, was not effective when the weeds were rank. Safflower desiccation is used to accelerate maturation of portions of fields where drying is delayed; in this crop weeds are rarely a problem in harvest. Sunflower desiccation has been attempted, but the heavy stalks, which are the principal source of difficulty in mechanical harvesting, were little affected by desiccants.

VI. Summary and Prospect

Defoliation is accelerated leaf fall and requires the functioning of living tissues at the leaf base. It is affected by many factors, internal and external. The principal internal factor is the hormone, auxin, the gradient of which across the leaf base regulates leaf fall. The principal external factors are temperature and moisture; defoliation is favored by relatively high temperature and moderate leaf moisture.

Defoliants appear to act through a mild general injury to both blade and petiole; they have no specific biochemical action.

Defoliation of cotton is an established practice in many regions and under some conditions, but is not necessary in other regions or under other conditions. Successful cotton defoliation requires careful attention in growing the crop and in applying the defoliant.

Desiccation is chemically accelerated drying of plants or plant parts and does not require active functioning on the part of the plant. Desiccants are essentially contact herbicides.

Desiccation has many potential advantages, and in a few crops it has become an established valuable practice. It is unnecessary where good cultural practices, favorable weather, and adequate time bring about the necessary drying; in most crops desiccation is of value only under limited conditions.

Premature application of either defoliant or desiccant risks serious losses in yield and quality.

Improvements in defoliants and desiccants will probably come slowly; present chemicals are relatively cheap, and although not perfect they are reasonably effective.

The prospect is that defoliation and desiccation will continue to be useful and important agronomic practices, valuable with certain crops under certain conditions. The end of exploratory work with these practices is probably near, since their advantages and disadvantages are now recognized.

New uses for defoliants and desiccants are probable as new crops or crop varieties are brought into regions where they grow well but where harvest is hampered by insufficient leaf fall or insufficient drying. The

steady development of mechanical harvesting and invention of new harvesting machinery probably will lead to greater use of both defoliation and desiccation.

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THE FIXATION OF PHOSPHORUS BY SOILS

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I. Introduction

The recovery of fertilizer phosphorus by the crop that is planted immediately after the fertilizer application amounts to only 10 to 30 per cent of the quantity added to the soil. The remaining 70 to 90 per cent has been assumed to be consumed by microorganisms, precipitated by soluble cations in the soil solution, or sorbed by the soil complex. It is now generally accepted that the part played by soil microorganisms is relatively minor, and that chemical precipitation and physicochemical sorption play the major roles. It is this phosphorus which has been rendered insoluble that is defined as "fixed," and with which we are concerned in this review.

Phosphorus fixation was first recognized in Europe around 1850, when it was reported that soil had the ability to "retain" phosphorus. Similar reports appeared in the United States shortly after 1900. However, in spite of this early recognition, the greatest strides in understanding the basic chemistry of this phenomenon and how to cope with it have been made only in the last 25 years.

The present literature on the fixation of phosphorus by soils gives a somewhat confusing picture regarding the reactions involved and the compounds formed. The most recent reviews on this subject are those by Wild (1949) and Dean (1949). Therefore, the emphasis in this re-

view will be on the literature appearing subsequent to 1949 with the purpose of presenting the new and modified concepts which have arisen.

II. Phosphorus Compounds in the Soil

Before discussing the reactions involved in phosphorus fixation, brief consideration should be given to the naturally occurring soil phosphorus compounds and to the forms of phosphorus which are added as fertilizers. Soils usually contain 0.10 to 0.25 per cent P_2O_5, and rarely more than 0.50 per cent. Generally speaking, inorganic phosphorus is the preponderant form of soil phosphorus, although soils exist in which as much as 75 per cent of the total phosphorus is in organic combination.

Almost without exception, the inorganic phosphorus exists entirely as salts of orthophosphoric acid. These salts can be classed generally as fluoro-, oxy-, and hydroxyphosphates of iron, aluminum, calcium, titanium, magnesium, and manganese. Buehrer (1932), using ionization constant data for H_3PO_4, has calculated that the predominant anion resulting from these compounds in the pH range of most soils would be $H_2PO_4^-$.

The amount of organic phosphorus in soils varies from 20 to 3500 pounds per acre. The principal groups of organic phosphorus compounds are the phospholipids, nucleic acids, inositol phosphates, "metabolic" phosphates, and phosphoproteins. In general, these compounds come from plant and animal residues and microorganisms, and are slowly mineralized to orthophosphate.

The major raw material for phosphorus fertilizers is rock phosphate, which is a composite of many minerals with fluorapatite ($(CaF)Ca_4(PO_4)_3$) predominating. This material is used directly as a fertilizer, although more commonly it is processed into a more soluble form by treatment with sulfuric acid and sold as superphosphate. This product is the major phosphorus fertilizer in use in the United States.

In recent years, with the demand for higher analysis fertilizers, there has been an increase in the production of concentrated superphosphates which are sold as double and triple superphosphates. These materials are prepared by treating rock phosphate with phosphoric acid rather than sulfuric acid.

The calcium orthophosphates are also widely used as fertilizers, especially in mixed fertilizers. The monobasic calcium phosphate ($Ca(H_2PO_4)_2$), which makes up about 80 per cent of the phosphorus in superphosphate, is the most soluble of the calcium phosphates. The dibasic calcium phosphate ($CaHPO_4$) and the tribasic calcium phosphate ($Ca_3(PO_4)_2$) are less soluble in the order mentioned and, therefore, are not used as frequently as the monobasic.

In addition to the orthophosphates mentioned, orthophosphoric acid is sometimes used in liquid fertilizer formulations. Also of minor importance as fertilizers are the sodium, potassium, and ammonium orthophosphates. The latter two are advantageous because they supply potassium or nitrogen in addition to phosphorus. These compounds also are found most frequently in mixed fertilizers.

Generally speaking, phosphorus is supplied to the soil as orthophosphate, and this is the most stable form in the soil. However, recently the Tennessee Valley Authority has been producing metaphosphate as a fertilizer. Although this material has not been used extensively, it compares favorably with superphosphate and seems to have a greater residual effect. Apparently the material must hydrolyze to orthophosphate before it becomes available to plants.

III. Phosphorus Fixation in Acid Soils

The subject of phosphorus fixation is most conveniently discussed as fixation under acid conditions and fixation under alkaline conditions, although it should be realized that the mechanisms mainly involved in each occur to some extent under both types of conditions. The components of acid soils that have been investigated to determine their role in phosphorus fixation can be divided conveniently into the compounds of iron and aluminum and the clay minerals. As will become evident, both these fractions fix phosphorus via essentially the same reactions.

1. The Role of Iron and Aluminum Compounds

The iron and aluminum oxides and hydroxides have been recognized by many workers as playing a significant role in phosphorus fixation. Toth (1937) demonstrated that the removal of the free iron oxide content of soil colloids reduces the magnitude of phosphorus fixation, and deduced from this that these compounds must be partially responsible for phosphorus fixation. Many other workers (Davis, 1935; Bear and Toth, 1942; Kelly and Midgley, 1943; Perkins and King, 1944; Kurtz *et al.*, 1946; Ensminger, 1948; Swenson *et al.*, 1949; Mattson *et al.*, 1950b; Struthers and Sieling, 1950; Bradley and Sieling, 1953; and Miller, 1954) also have postulated and demonstrated that iron oxides and aluminum oxides play an important role in phosphorus fixation, but only recently has there been a real effort made to identify the compounds formed and the mechanisms involved.

Most workers agree that it is unlikely that the formation of iron and aluminum phosphate ($FePO_4$ and $AlPO_4$) accounts for much phosphorus fixation. Swenson *et al.* (1949) obtained potentiometric titration curves for iron and aluminum chlorides in the presence of varying

amounts of phosphate. Their curves indicated that in the pH range of acid soils, the compounds formed are Fe or $Al(H_2O)_3(OH)_2H_2PO_4$ rather than Fe or $AlPO_4$.

Haseman *et al.* (1950b), using electron and x-ray diffraction techniques, made a mineralogical classification of the compounds formed by the reactions of iron and aluminum with phosphate in the presence of the common soil cations. The compounds found were all iron and aluminum oxy- and hydroxyphosphates in which isomorphous substitution of iron and aluminum was common. However, the conditions of the experiment did not closely parallel soil conditions, and the authors admitted that there were no techniques available for isolating these compounds from the soil to determine if they exist there.

At the same time that Haseman *et al.* (1950b) published their paper, Cole and Jackson (1950a,b) published two papers describing studies in which the experimental techniques used were similar to those of Haseman *et al.* The first of these papers (Cole and Jackson, 1950a) contained evidence that the iron and aluminum phosphate precipitates formed at room temperature are crystalline, and are the same species as are formed by digestion at hot plate temperatures. They stated that this relationship constituted the first direct evidence of the particular crystal species of aluminum and iron phosphate probably precipitated under acid soil conditions, namely, members of the variscite-barrandite-strengite isomorphous series, which are aluminum and iron dihydroxy dihydrogen phosphates, and sterrittite, an aluminum dihydroxy (mono-di)-hydrogen phosphate.

In their second paper, Cole and Jackson (1950b) determined the solubility constants of these compounds at equilibrium and showed that these constants relate the equilibrium concentration of phosphorus in solution directly to the aluminum and iron activity of the solution. The authors felt that the equilibrium constants were of such magnitude as to account for the formation of iron and aluminum hydroxy phosphates in acid soils to which soluble phosphate fertilizers are added. Although the soil is a much more complex system than those with which Cole and Jackson worked, it is reasonable to believe that the principles illustrated do apply in the soil.

Recently Kittrick and Jackson (1955a–c, 1956) published a very interesting series of papers in which they explained phosphorus fixation on the basis of the solubility product principle. In the first of these papers (Kittrick and Jackson, 1955a), they show electron microscope pictures of aluminum and iron oxide surfaces in contact with phosphate solutions. The pictures show quite dramatically that with time the iron or aluminum oxide phase disappears and a separate iron or aluminum hydroxy phosphate phase forms. They cited this observation as evidence

that a solution-precipitation mechanism is operative in phosphorus fixation.

In the second and third papers (Kittrick and Jackson, 1955b,c) of this series they explained the divergence between the phosphate concentration supported by various precipitated phosphate compounds in pure water and the known soil solution phosphate concentration on the basis of the solubility product principle. As evidence in support of this explanation, they showed that the addition of any iron- or aluminum-containing minerals to an equilibrium solution of an iron or aluminum phosphate decreased the concentration of phosphate in the solution although the solubility product remained essentially constant. These papers by Kittrick and Jackson are very significant in that they contain examples of some of the first quantitative evidence to show that phosphorus fixation can be explained on the basis of the solubility product principle.

The experimental techniques described in the papers just discussed required that the iron and aluminum phosphate compounds formed be precipitated. However, these results do not exclude the possibility that these compounds, once formed, also can be adsorbed by the colloidal inorganic fractions of the soil by van der Waals' forces. Whether the compounds formed are precipitated or adsorbed, the solubility product should be essentially the same. The important point is that phosphorus is fixed as a highly insoluble compound with iron or aluminum which is probably both precipitated and adsorbed under soil conditions. It should also be pointed out (Miller, 1954) that these iron and aluminum phosphate compounds, once they are precipitated or adsorbed, can adsorb $H_2PO_4^-$ ions in a manner analogous to the adsorption of Cl^- by AgCl precipitates, especially if the particles of the precipitate are colloidal in size. However, this latter consideration is secondary to the basic compound formation.

Since the phosphorus fixation reaction is so often characterized by the Freundlich adsorption isotherm, mention should be made of the reliability of this. Fisher (1922) has pointed out that the Freundlich adsorption isotherm is of value only in characterizing a known adsorption reaction, and does not constitute indisputable evidence that an unknown reaction is an adsorption. Since many precipitation reactions can be characterized by this isotherm, it is fallacious to characterize phosphorus fixation as adsorption on the basis of compliance with the Freundlich adsorption isotherm alone.

2. *The Role of Clay Minerals*

The reactions of phosphorus with the clay minerals in soil have also received a great deal of attention from soil scientists. Although in this

review the role of the iron and aluminum compounds in phosphorus fixation has been discussed separately from the role of the clay minerals, it is becoming increasingly evident that both fix phosphorus by essentially the same mechanisms. As a matter of fact, it is probably the aluminum in and on the clay that is responsible for the phosphorus-fixing property of clay.

Most investigators have not considered the possibility that aluminum from the clay minerals could be appreciably responsible for the ability of clay to fix phosphorus. Yet as early as 1934, Paver and Marshall (1934) presented evidence which indicated that supposedly hydrogen-saturated clays were in reality mixed hydrogen and aluminum clays. Again, in 1946, Schofield [quoted from Russell (1950), pp. 95–96] suggested that an aluminum or aluminum hydroxide coating developed on clay minerals as a result of their decomposition. About this same time, Mukherjee *et al.* (1947, 1948) showed that clay minerals yielded Fe^{+++} and Al^{+++} upon repeated washing with salt solutions. Recently Harward and Coleman (1954) and Low (1955) showed, by potentiometric and conductometric titration curves, that H-clays were actually H-Al-clays and that the aluminum came from the clay lattice. Klages and White (1957) presented evidence that a partially hydrated aluminum hydroxide exists as an interlayer material in clays extracted from weathered soils.

Sieling (1946) showed that ball-milling or alkali treatment of kaolinite results in a material which does not have the properties of kaolinite, but contains a large amount of aluminum which he believed to be gamma-AlOOH. This treated kaolinite has the ability to fix far more phosphorus than untreated kaolinite. Perkins *et al.* (1955) observed the same effect upon ball-milling kaolinite for 21 weeks. The decomposition of kaolinite in soil by methods producing the same results as ball-milling or alkali treatment undoubtedly proceeds at a slow rate, but the fact is that clays are a potential source of aluminum.

Coleman (1944a,b) was the first soil scientist clearly to postulate that phosphorus fixation by clay minerals is due to the aluminum content of the clays and has nothing to do with the intact clay minerals. He showed that the amount of phosphorus fixed by clays is proportional to the amount of free aluminum oxides on the clays, and that fixation occurs only as long as this aluminum is present. He also presented much indirect evidence which lends support to his arguments but does not constitute irrefutable proof. Nevertheless, Coleman's interpretations were sound, as has been revealed by more recent evidence.

Through fixation studies with the clay minerals montmorillonite, illite, and kaolinite and the minerals gibbsite ($Al(OH)_3$) and goethite ($Fe(OH)_3$), Haseman *et al.* (1950a) showed that the mechanism of

fixation by each of these minerals was identical. All were characterized by two stages of fixation, one progressing at a rapid rate and one at a much slower rate. They concluded that both stages of fixation proceed through the same chemical reaction, that the rapid fixation results from the reaction of phosphate with readily available aluminum and iron, and that the slow fixation results from the reaction with aluminum and iron released through decomposition of the respective minerals.

Low and Black (1947) adopted a unique approach to the problem of phosphorus fixation by kaolinite. They hypothesized that kaolinite dissociates into aluminum and silicate ions in accordance with the solubility product principle and that phosphate precipitates the aluminum, thereby disturbing the equilibrium and causing more clay to dissolve. As evidence in support of the hypothesis, it was found that the addition of both phosphate and 8-quinolinol to kaolinite produced a considerable increase in the concentration of silica in the solution. This same effect has been demonstrated more recently for both soils and clay minerals by Reifenberg and Buckwold (1954). Kittrick and Jackson (1954), by the use of electron micrographs and x-ray diffraction, have shown that kaolinite will "dissolve" in the presence of phosphate at 90° C. and that an aluminum phosphate is formed leaving no traces of kaolinite after 31 days. In the experiments of both Low and Black, and Kittrick and Jackson, the phosphate concentrations used were high. However, this would only cause the reaction to occur at a faster rate than under normal soil conditions.

Later Low and Black (1950) showed that at lower phosphorus concentrations fixation by kaolinite obeys the Freundlich adsorption isotherm and increases with temperature. From this they concluded that the adsorption was a chemisorption and that the reaction was between the phosphate and the surface hydroxyl ions of the clay mineral. However, Russell and Low (1954) repeated much of this work and demonstrated that the presence of aluminum ions adsorbed on the clay was necessary for the clay to fix phosphorus. From these studies they concluded that the reaction was between the phosphate and the adsorbed aluminum.

Additional support for the hypothesis that aluminum is necessary for clay minerals to fix phosphorus was provided by Ellis and Truog (1955) and Wey (1955). Ellis and Truog (1955) found that montmorillonite will not fix phosphorus once all iron and aluminum has been removed from the clay. Wey (1955) found that the presence of fluoride or ammonium aurin tricarboxylic acid (aluminon), both strong complexing agents for aluminum, inhibits the fixation of phosphorus by montmorillonite. In addition, he further showed by x-ray diffraction evidence that fixed phosphorus is not sorbed between the lamellae of

the clay minerals and does not interfere with the swelling properties of the clay. His most interesting experiment was one in which he demonstrated that hectorite (Mg substituted for Al in the octahedral position of montmorillonite) does not fix phosphorus.

In an effort to characterize the reaction of phosphate with clays more quantitatively, Hemwall (1957) measured the solubility of both kaolinite and montmorillonite clays and of the resultant aluminum phosphate. He found that clays which were capable of fixing phosphorus supported a higher soluble aluminum concentration than the resultant aluminum phosphate. In addition, the solubility product of the aluminum phosphate was constant, regardless of type of clay, concentration of phosphate, or time of contact between clay and phosphate, indicating the formation of a definite compound. He thus concluded that phosphorus is fixed by clay minerals by reacting with soluble aluminum, which originates from the exchange sites and from lattice dissociation of the clay minerals, to form a highly insoluble aluminum phosphate compound.

Recently Fried and Dean (1955) determined the phosphorus-fixing characteristics of iron- and aluminum-saturated cation exchange resins. They found that these materials were capable of fixing phosphorus and concluded that a similar phenomenon could occur in the soil via the clay minerals. They further showed by exchange studies using radioactive phosphorus that the fixed phosphorus was similar both on the ferrated exchange resin and on the clay minerals. Thus, they concluded that adsorbed iron and aluminum ions on clay minerals were at least partially responsible for phosphorus fixation.

Fried and Dean (1955) also presented data which showed that 75 per cent of the phosphorus retained by the ferrated exchange resin was readily exchangeable with radioactive phosphorus. They stated that this is an " . . . improbably high exchangeability for a precipitate," and, hence, must be an adsorption. They believe that this adsorption is probably an anion exchange reaction. However, adsorption of the iron phosphate compound formed would lead to the same experimental results. The writer is of the opinion that the latter explanation is more consistent with the bulk of experimental evidence.

Thus far the literature reviewed has indicated that the clay minerals as such are not active in phosphorus fixation. However, it has been suggested in a number of papers that phosphorus is fixed by an exchange of the phosphate ion for the structural hydroxyl ion on the surface of clay minerals. The data presented as evidence for this concept can be explained on the basis of the previously discussed concepts.

In 1934, Ravikovitch (1934) hypothesized this concept of "anion exchange." As evidence for his hypothesis, he cited data that showed

that as the pH of a soil was increased, the amount of phosphate in solution increased. He concluded that because of the increased concentration of hydroxyl ions, the hydroxyl ions were replacing the phosphate ions on the clay surface. In the light of the previous discussion, his observations can be explained on the basis of decreased solubility of the iron and aluminum oxides and hydroxides present in the soil, thus increasing the amount of phosphorus in solution.

Stout (1939) and Kelly and Midgley (1943) showed that when phosphate is added to clay there is an increase in the hydroxyl ion concentration. They cited this as evidence for phosphate's replacing hydroxyl ions from the clay surface, although the same effect would be expected from a reaction between phosphate and aluminum or iron hydroxide. Dickman and Bray (1941), supporting the same hypothesis, showed that fluoride will replace phosphate. Fluoride would replace phosphate from aluminum phosphate also.

Some very elaborate and interesting physical chemical methods were used by McAuliffe *et al.* (1947) in an effort to further the hypothesis of anion exchange via surface hydroxyls of clay minerals. In their first series of experiments the authors showed that the exchange of P^{32}, which had been added to the phosphate solution in equilibrium with a soil sample, proceeded in two steps. The initial step was very rapid, and the latter step was slow. They attributed the rapid exchange to the anionically held phosphate, and the slow exchange to an undetermined reaction. These data are inconclusive in that there are other explanations for them. One alternative explanation is that the initial rapid exchange was between the already fixed phosphorus and the P^{32} in solution, and that the subsequent slow exchange was actually due to the fixation of more phosphorus, both P^{31} and P^{32}. McAuliffe *et al.* (1947) presented no evidence that would refute this latter explanation, and it is more compatible with the often observed fact that clays will continue to fix phosphorus at a very slow rate over long periods of time.

In the second part of their paper, McAuliffe *et al.* (1947) tried to measure the surface hydroxyl ions on a number of soil minerals by exchange with the deuteroxyl ion. However, in a number of cases they obtained greater surface areas by this technique than they did by adsorption of ethane using the BET theory (Brunauer *et al.*, 1938). Further, there is no reason to believe that there would be a direct relationship between isotopic exchange and the exchange of one ion for another. These latter data also appear to be inconclusive.

Dean and Rubins (1947) also wrote of anion exchange of phosphate. From the fact that chelating agents would free phosphorus they realized that some phosphorus was fixed by methods other than anion exchange,

namely, by combination with aluminum or iron. For the most part, the anion exchange theory of phosphate fixation today has very few supporters.

Before leaving the discussion of clay minerals, it should be noted that there is a possibility of phosphorus being sorbed by an anion exchange process at the lattice edges of the clay plates. Although no experimental work along this line has been reported, van Olphen (1950, 1951) has hypothesized the existence of a positive layer with negative diffuse ions at the edges of clay minerals, which would operate similarly to the double layer on the planar surfaces of the clay minerals. Such a layer as this would make it possible for clays to adsorb phosphorus by anion adsorption. However, the extent of this fixation would undoubtedly be small.

It can be concluded that phosphorus fixation in acid soils is primarily due to the formation of iron and aluminum compounds of the nature $M(H_2O)_3(OH)_2H_2PO_4$. The iron- and aluminum-containing soil minerals, including the clay minerals, are the source of the iron and aluminum. The formation of these compounds is governed by the solubility product principle, the common ion principle, and the salt effect principle. Under certain conditions, the compounds form a precipitate, whereas under other conditions, they are adsorbed. Regardless of whether the compounds are adsorbed on the surface of a soil mineral or precipitated, the compounds formed and the mechanism of reaction seem to be essentially the same. In a generalized manner, the fixation of phosphorus in acid soils can be visualized as follows:

$$
\begin{array}{ll}
(M(H_2O)_xA_y)^{+3 \text{ to } +1} + A + H_2PO_4^- \leftrightarrows & (M(H_2O)_xA_zH_2PO_4)\downarrow \\
\quad\upharpoonleft\!\downharpoonright & \\
M_2O_3,\ M(OH)_3, & \\
\text{Clay Minerals, and} & \text{Precipitated or} \\
\text{Exchange Sites} & \text{Adsorbed}
\end{array}
$$

in which the symbol M stands for the cations of iron or aluminum and the symbol A stands for oxide or hydroxide.

IV. Phosphorus Fixation in Alkaline and Calcareous Soils

Phosphorus fixation in alkaline and calcareous soils is usually attributed to the formation of phosphate compounds of calcium. In addition, however, the iron and aluminum compounds discussed in relation to fixation in acid soils are also responsible for some fixation in soils of higher pH. Although calcium has been known for a long time to be a factor in causing fixation in high pH soils, the exact compounds formed are still unknown. In addition, this problem has no ready solu-

tion because of the chemical nature of the calcium phosphates. As pointed out by Eisenberger *et al.* (1940), between the compounds $CaHPO_4$ and CaO there exists a continuous series of solid solutions having an apatite ($(CaF)Ca_4(PO_4)_3$) structure. In addition, the structure of apatite is remarkably stable, permitting a number of unusual types of substitutions and involving a considerable number of ions. Therefore, it is only a fortuitous occurrence when the composition of any calcium phosphate can be expressed by small whole number ratios of atomic species suggesting a definite chemical compound. Further, as pointed out by Mattson *et al.* (1951), the calcium phosphates can adsorb additional phosphate, thus creating more complicated systems. It is obvious that in a highly complex medium like soil, the identification of any specific compound is likely to be difficult and of dubious value.

Burd (1948), working with calcareous soils, pointed out that the very general occurrence of potentially soluble calcium compounds in soils and the relatively low solubility of the calcium phosphates would lead to the formation of some form of calcium phosphate upon the addition of phosphatic fertilizers. He showed that the concentration of calcium in the soil solution is the dominant factor in determining phosphate concentration in the liquid phase of the soil, thus confirming the role of calcium in phosphorus fixation.

Buehrer (1932) treated the hypothetical system $CaHPO_4$-$CaCO_3$-H_2CO_3 quantitatively in the light of solubility products, ionization constants, and the principle of the ionic strength. His prediction that the phosphate concentration in solution is directly proportional to the hydrogen-ion concentration, inversely proportional to the calcium-ion concentration, and increased by the presence of ions that decrease the ionic strength of calcium was borne out by his observations.

In addition to the phosphorus fixed by the calcium compounds in the soil, it also has been suggested that adsorbed calcium on the clay minerals could fix phosphorus. Pratt and Thorne (1948) showed that calcium-saturated clays fix far more phosphorus in the alkaline range than sodium-saturated clays. Further, as pH is increased, the calcium clay fixes more and more phosphorus, as would be expected from the decreasing solubility of calcium phosphates with increasing pH. Pratt and Thorne did not present any information as to whether the calcium phosphate thus formed is precipitated as a distinct phase or is sorbed on the surface of the clay particles.

Klechkovskii and Zherdetskaya (1951), using radioactive phosphate, showed that regardless of the state of calcium in the soil—whether completely adsorbed or displaced by potassium—the amount of "sorbed" radiophosphorus remained constant, and that fixed phosphate

ions were equally capable of isotopic displacement. Since the calcium phosphates formed in both instances were so similar, these authors concluded that the existence of a clay-calcium-phosphate "bridge" cannot be regarded as possible and that a more logical explanation in both cases would be the formation of a precipitate.

Recently Wild (1953) presented a somewhat different approach to the role of clay minerals in phosphorus fixation in alkaline soil. He suggested that the exchangeable cations determine the extent of formation of basic aluminum phosphate, the aluminum being present as an $Al(OH)_3$ on the clay. His evidence was that an increase in phosphorus retention was found with monovalent as well as with divalent cations, thus ruling out the clay-cation-phosphate "bridge" explanation, since this is unlikely to occur with monovalent cations. Further evidence was that the cation effect on retention was found with an aluminum-saturated exchange resin, but not with a hydrogen resin or an aluminum sulfate solution. This latter evidence indicated that it was the exchangeable aluminum which was being affected by the exchangeable cations. Wild did not present any evidence as to the mechanism of this cation effect.

It can be concluded that in calcareous and alkaline soils, the fixation of phosphorus is due to the formation of a whole series of insoluble calcium phosphate compounds. These compounds form solid solutions and are rather difficult to characterize chemically, as they tend to be quite heterogeneous. Further, there is evidence that phosphorus can be fixed by the Al^{+++} or $Al(OH)_3$ in the clay fraction of alkaline soils, this fixation being partially a function of the other cations present.

V. Fixation of Organic Phosphorus

As was pointed out in an earlier section, organic phosphorus compounds generally represent only a small portion of the total soil phosphorus. In addition, it is usually considered that plants derive their phosphorus only from inorganic sources and that the organic phosphorus compounds must be mineralized before they are plant available. Further, aside from manure, organic phosphorus fertilizers are not in use. Therefore, it is not surprising that there is a relative dearth of literature concerning the fixation and reactions of this class of compounds in soil.

Several organic phosphorus compounds, including several naturally occurring compounds, were tried as fertilizers, by Spencer and Stewart (1934), Bertramson and Stephenson (1942), and MacIntire *et al.* (1948). All these workers concluded that although the organic phosphorus compounds were satisfactory sources of phosphorus, generally

they were not as efficient as the usual inorganic sources. Whether or not the organic compounds used were mineralized prior to being adsorbed by the plant was not definitely concluded from these experiments.

Bower (1949) reported an extensive series of experiments concerning the forms and availability of naturally occurring soil organic phosphorus. He concluded that phytin, nucleic acids, and their respective derivatives are the major forms of soil organic phosphorus. In addition, direct evidence was obtained for the mineralization of these compounds during incubation, hence confirming the probability that this is one method by which plants utilize organic phosphorus. Further work along this line by Eid *et al.* (1951) indicated that this method is the predominant, if not the only, method by which plants obtain phosphorus from naturally occurring organic phosphorus. In addition, Eid *et al.* found that this mineralization was quite significant at higher soil temperatures (35° C.), whereas at lower soil temperatures (20° C.) it did not represent a significant contribution to the phosphorus supply.

Additional experiments by Bower (1949) showed that soil conditions which influence the fixation and availability of both phytin and inorganic phosphorus are similar. This is very reasonable when it is considered that phytin forms highly insoluble salts with iron, aluminum, and calcium. He also found that nucleic acids were adsorbed by clay minerals. This adsorption increased with decreasing pH and was greater on bentonite than on kaolinite. These facts correlate quite well with the increasing basicity of these compounds as acidity increases and with the higher exchange capacity of bentonite. The important point is that these two classes of organic phosphorus compounds are both fixed by soils, though by basically different mechanisms.

Goring and Bartholomew (1952) further characterized the adsorption of nucleic acids by clay minerals. They showed that the adsorption was reversible, was linearly related to the cation exchange capacities of the various clay fractions, and took place at least partially between the silicate layers. From this, it was concluded that the nucleic acids were adsorbed via a cation exchange reaction. The fact that adsorption was greater in the presence of calcium and magnesium ions than in the presence of sodium or potassium ions indicated some additional reaction between the divalent cations and the orthophosphate groups of the nucleic acids.

Although there is a lack of extensive critical evidence concerning the fixation of organic phosphorus by soils, a few general conclusions can be reached. Certain organic compounds, notably phytin and its derivatives, form insoluble aluminum, iron, and calcium compounds in a manner similar to orthophosphate. In addition, other compounds

possessing a basic or cationic character, namely, nucleic acids and their derivatives, are adsorbed by a cation exchange mechanism. The author believes that sorption due to van der Waals' forces also accounts for some organic phosphorus fixation, although he is not aware of any evidence on this point.

VI. The Plant-Soil Phosphorus Relationship

In order to understand some of the implications of the phosphorus fixation processes, consideration should be given to the relationships that exist between plant roots and soil phosphorus. As matters presently stand there is no generally accepted composite picture of the processes taking place during phosphorus absorption by plants, although recent reviews by Overstreet and Jacobson (1952) and Robertson (1951) have shown the development in the understanding of the mechanisms of ion absorption by roots. There is also a lack of critical investigation as to what phosphorus compounds plants will utilize or even prefer. It is generally conceded that the form of phosphorus used by plants is $H_2PO_4^-$, the predominant anion form. However, this does not preclude the possibility that plants could obtain their phosphorus from other compounds or ionic species.

It has been observed repeatedly that plant response to soil phosphorus is a function of the solubility of the phosphorus present, and that any factor altering this solubility will alter the plant response. Pratt and Thorne (1948) demonstrated this and further showed that phosphate availability was subject to explanation by the common ion principle. Starostka and Hill (1955) recently confirmed the work of Pratt and Thorne and demonstrated that the salt effect could be used to explain increases in phosphorus availability. Some 25 years ago Buehrer (1932), on the basis of theoretical calculations, predicted that these two effects on solubility should govern phosphorus availability to plants.

In addition to recognizing the soil factors which influence the solubility of phosphorus, Drake and Steckel (1955) proposed some mechanisms by which plants can influence soil phosphorus solubility. These authors showed that the higher the cation exchange capacity of plant roots, the more effective is the plant at utilizing both applied rock phosphate and natural soil phosphorus. The two mechanisms believed to be involved are (*1*) the reduction of the calcium activity in the soil solution via the bonding of calcium by the plant root exchange sites, thereby resulting in an increased phosphate activity in the soil solution and concomitant increase in phosphorus uptake and (*2*) the reduction of the iron and aluminum activity in the soil solution via the

complexing of these cations by root-exuded organic anions, resulting, as before, in increased phosphate activity and uptake. Whether or not these two mechanisms are as distinctly different as presented is a moot point. However, the principles involved provide logical explanations for the differing abilities of plants to obtain phosphorus from the soil.

Although it is generally believed that plant roots obtain their phosphorus from the soil solution, Islam (1955, 1956) has hypothesized that plants can also obtain phosphorus from the soil solid phase via a contact exchange mechanism similar to that proposed for cations by Jenny and Overstreet (1939). In the first of these papers Islam (1955) reported a series of experiments in which he grew normal plants in a soil from which he could leach no phosphorus with water, CO_2-saturated water, Hoagland's solution, and 0.01 N HNO_3. He concluded that solubility was not the only criterion of phosphorus availability. However, the author stated that the soil he used " . . . was selected for this study because it is notorious for its high phosphate-adsorption capacity . . . " He failed to consider that his leaching technique may have merely transferred the phosphorus from those micro-areas where, because of the presence of phosphorus fertilizer, the conditions were such that there was enough phosphorus in solution for the plants, to other micro-areas where it became "fixed," with the result that no phosphorus appeared in his leachate. This latter explanation seems especially plausible for a soil " . . . notorious for its high phosphate-adsorption capacity . . . "

In a further attempt to advance his hypothesis, Islam (1956) conducted a series of experiments in which lettuce plants were grown either in a dilute soil suspension (0.4 per cent) or in a phosphate solution. The concentration of phosphorus in the solution was adjusted so that it equalled the concentration in the intermicellar liquid of the suspension. On the basis of the fact that the lettuce plants growing in the suspension absorbed the most phosphorus, he concluded that some contact exchange phenomenon was occurring. However, the fact that the suspension contained some insoluble phosphorus in addition to that in solution, which would constantly be equilibrating with the solution, cannot be overlooked. The higher "average" level of soluble phosphorus in the suspension could well be the reason for his results.

Dean and Rubins (1945) conducted a less ambiguous experiment somewhat similar to Islam's (1956), from which they concluded that contact exchange is not a factor in phosphorus nutrition of plants. This experiment involved growing plants in soil suspensions either directly or with the plant roots enclosed in collodion bags so that there was no direct contact between the roots and soil particles. This experimental device made it possible to maintain equal phosphorus concentration

both in the suspension intermicellar solution and in the pure solution throughout the duration of the experiment. The results showed equal phosphorus uptake from both the suspension and the solution, thus leading the authors to their conclusion that contact exchange does not contribute to phosphorus uptake.

Mattson *et al.* (1949, 1950a,b, 1951, 1953a,b), Wiklander (1950), and Miller (1954) presented comprehensive theoretical treatments of the availability of phosphorus to plants. These authors postulated that an electrical double layer exists at the insoluble phosphorus-soil solution interface and at the soil solution-plant root membrane interface, and that the distribution of ions between the interface, diffuse double layer, and solution is governed by the Donnan equilibrium principle. Although there are usually difficulties inherent in making physical models of biological systems, this approach may be necessary to obtain more quantitative information concerning the root-soil relationship.

VII. Summary

The insoluble phosphorus compounds present in soils can be classed generally as the oxy- and hydroxyphosphates of Fe^{+3}, Fe^{+2}, Al^{+3}, Ca^{+2}, Ti^{+4}, Mg^{+2}, Mn^{+2}. The predominant soluble phosphorus ion present in the soil solution is $H_2PO_4^-$, and it is generally conceded that this anion is the source of phosphorus used by plants.

Phosphorus fixation in acid soils is due to the formation of insoluble iron and aluminum compounds of the nature of $M(H_2O)_x(OH)_yH_2PO_4$. The iron- and aluminum-containing soil minerals, including the clay minerals, are the source of the iron and aluminum. The formation of these compounds is governed by the solubility product, the common ion, and the salt effect principles. Under certain conditions, a precipitate is formed, whereas under other conditions the compounds are adsorbed.

In calcareous and alkaline soils, the fixation of phosphorus is due to the formation of a whole series of insoluble calcium phosphates. These compounds form solid solutions and are rather difficult to characterize chemically, as they tend to be quite heterogeneous. There is also evidence that phosphorus can be fixed by the Al^{+3} or $Al(OH)_3$ in the clay fraction of alkaline soils, this fixation being partially a function of the other cations present.

Organic phosphorus compounds are also fixed in the soil. Certain compounds, notably phytin and its derivatives, form insoluble aluminum, iron, and calcium compounds in a manner similar to orthophosphate. In addition, other compounds possessing basic or cationic characteristics, namely, nucleic acids and their derivatives, are adsorbed by a cation exchange mechanism.

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THE LESPEDEZAS

Coordinated by Paul R. Henson

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I. The Origin, History, and Development of Lespedeza in the United States

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1. Introduction

The lespedezas have become, in a relatively short time, the most important summer-growing legumes for pasture, hay, and soil improvement in the southeastern states. Their popularity is due to their ability to grow and produce abundantly in acid soils varying in texture from sands to heavy clays and in fertility from eroded or even abandoned hillsides to reasonably fertile bottomlands.

The lespedezas differ from most of our other forage legumes in that they are warm-season plants and grow well only during the summer months. Seedling plants of the annuals or new shoots of the perennial lespedezas emerge as the frost-free period begins in the spring, grow through the summer, and produce seed in late summer or early fall depending on the species, management, and location. Permanent pastures of the region are usually unproductive from midsummer to early fall, a period when lespedeza is most productive. In favorable years when there is an abundance of pasturage, the lespedeza may be cut for hay, harvested for seed, or turned under as a soil-improving crop. The lespedezas are easily established and once established, will reseed under proper management.

2. Origin and Species

The lespedezas are native to eastern Asia and the southeastern part of the United States. Of approximately 140 species which have been described, 125 are of Asiatic origin and 15 are native to the United States (Schindler, 1913; Nakai, 1927; Small, 1933). Many of the species have not been intensively studied, and it is probable that some reported as species are forms of the same species. Although predominantly of Asiatic origin, it is of interest to note that the genus name *Lespedeza* was first applied by a French Botanist to the American species (Ricker, 1930) in honor of the Spanish Governor Céspedez of the Florida Colony from 1784 to 1790.

The species of Lespedeza were classified and grouped into three sections taxonomically (Maximowicz, 1873). Space will not permit a detailed discussion of each section. As new species have been discovered, they have been described under appropriate sections. The sections of the *Lespedeza* genus and the approximate number of species in each is as follows:

Section I. *Archilespedeza* Taug.		84 species
Subsection *Macrolespedeza* Maxim.	46 species	
Subsection *Eulespedeza* Maxim.	38 species	
Section II. *Campylotropis* Bge. (al Gatt.)		54 species
Section III. *Microlespedeza* Maxim.		2 species

The species, a total of 138, in Sections I and II are all perennial and are either shrubby or herbaceous in growth. All the American species and a number of those from Asia are herbaceous, their annual growth dying to the ground each year. Seed of the species in the Eulespedeza subsection and the Microlespedezas are produced from both cleistogamous or small, inconspicuous flowers and chasmogamous or showy, pea-type flowers. Seed from cleistogamous and chasmogamous flowers differ markedly in *Lespedeza cuneata* (Fig. 1). The flowers of all other species are of the chasmogamous or showy type only.

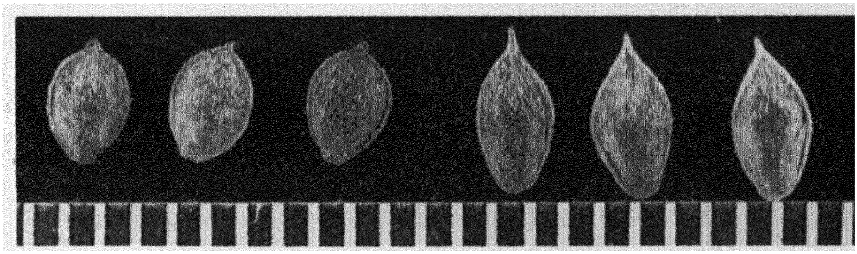

FIG. 1. Unhulled seed of *Lespedeza cuneata* from cleistogamous flowers—left, and from chasmogamous flowers—right.

The two species in Section III, Microlespedeza, *L. stipulacea* Maxim., and *L. striata* (Thunb) Hook & Arn., are the only annuals in the genus. *L. stipulacea* differs from *L. striata* in having much broader leaflets and stipules. Flowers and seed are borne in leaf axils at the tips of stems in *L. stipulacea* in contrast to the habit of flowering in leaf axils all along the stem in *L. striata.* At maturity the leaves of *L. stipulacea* turn forward so that the tips of the branches resemble small cones. This does not occur in *L. striata.* Another distinguishing characteristic is that the hairs on the stems of *L. stipulacea* are appressed upward, whereas those of *L. striata* are appressed downward.

The herbaceous perennial lespedeza, *L. cuneata* (Dum. de Cours.) G. Don, and closely related species in the Eulespedeza section are of increasing importance to agriculture in the southeastern states. *L. cuneata,* first introduced from Asia as *L. sericea,* is now commonly known as sericea lespedeza throughout the lespedeza region (Pieters *et al.,* 1950). *L. cuneata* and its closely related species form the sericea group. Because of their potential value this group has been studied more intensively than other species. In unpublished results of species

classification studies made in the field from 1935 to 1940, P. L. Ricker and Roland McKee, then Research Botanist and Research Agronomist, respectively, of the U.S. Department of Agriculture, found intermediate types within the species, making it very difficult to classify plants properly according to species. To expedite classifications, they developed a tentative key based largely on vegetative characters to distinguish between species. The key is as follows:

1. Long slender racemes.......... *tomentosa* (Thunb.) Sieb.

2. Short dense racemes
- Stem pubescence not spreading
  - Calyx teeth not conspicuously veined, 2–4 flowers
    - Stem erect, calyx teeth longer than tube, leaf venation 30°
      - Leaflet cuneate, truncate at tip.............. *cuneata* (Dum. de Cours.) G. Don
      - Leaflet oblanceolate, rounded at tip, mostly glabrous............. *juncea* (Willd.) Pers.
      - Leaflet linear cuneate.... *caragana* Bunge
    - Stem prostrate, calyx teeth equal to tube.......... *latissima* Nakai
  - Calyx teeth conspicuously veined, 6–20 flowers
    - Calyx teeth broadly subulate, 6–8 flowers, venation 45°
      - Leaflet acute at both ends *hedysaroides* (Pallas) Kitagawa
      - Leaflets rounded above, narrowing below, upper branches not widely spreading .... *inschanica* (Maxim.) Schindl.
    - Calyx teeth linear subulate, 12–20 flowers, leaflet venation 80°
      - Plant erect, calyx teeth equal to corolla....... *daurica* (Laxm.) Schindl.
      - Plant prostrate, calyx teeth exceeding corolla *daurica schimadai* (Masam.) Masam. et Hosok.

The two forms of *Lespedeza daurica* have coarse stems, relatively few in number, and coarse leaves. Seed production is abundant and the species may have value as food for wild life. *L. tomentosa* is a

coarse, erect plant. With the possible exception of the use of seeds by game birds these two species do not appear to be of economic importance.

A number of the shrubby species such as *L. bicolor* Turcz., *L. thunbergii* (D.C.) Nakai, *L. cyrtobotrya* Miq., and *L. japonica* L. H. Bailey, have value as ornamentals or for soil conservation and as a food for wild life. *L. bicolor*, now known as bicolor lespedeza, is highly valued for soil conservation and as quail food (Davison, 1948). NATOB, an early-maturing variety of bicolor lespedeza, developed and released by the Soil Conservation Service, U.S. Department of Agriculture, is being used for erosion control and as a food for wild life in the more northern part of the lespedeza region (Crider, 1952).

3. *History*

In 1846, a plant sent in from Jasper County, Georgia, by Thomas C. Porter was identified at the Gray Herbarium of Harvard University, Cambridge, Massachusetts as *Lespedeza striata*. This is the earliest record of this species in the United States (Pieters, 1934). Nothing is known of how this Asiatic species reached the United States, but it is thought to have come over in tea shipment packing from China. During the next 20 years *L. striata* spread over many of the southern states, possibly aided by cavalry movements during the Civil War. Following the Civil War a number of men who appreciated the potential value of lespedeza, as indicated by their communications and by distribution of seed, were instrumental in bringing about greater usage of the crop. To mention a few of these men, in 1867 the Rev. Grove A. Carteledge of Georgia, observing that cattle relished lespedeza, distributed seed to interested farmers (Pieters, 1934). Col. J. B. McGehee of Laurel Hill, Louisiana, in 1880 found lespedeza to be an excellent hay plant and strongly recommended it for hay to Louisiana farmers. In 1887, A. P. Rowe and A. W. Boalware, both of Fredericksburg, Virginia, stressed the value of the crop on the worn soils of eastern Virginia.

In 1919 two new introductions of lespedeza were received which were greatly to expand the lespedeza acreage. A plant explorer for the United States Department of Agriculture, J. B. Norton, found a tall, vigorous, late-maturing plant of *L. striata* growing near Kobe, Japan. This strain, later named Kobe lespedeza, was first grown at Hartsville, South Carolina, where it was found to be much more productive than the common lespedeza then being grown. The first seed crop was produced by the Coker Seed Company of Hartsville. Within a short time Kobe lespedeza became widely accepted across the lower half of the lespedeza region (McKee and Hyland, 1944). Also in 1919, a packet of seed of the other species of annual lespedeza, *L. stipulacea*, was received from a medical missionary, Ralph G. Mills, from near Seoul, Korea.

This introduction, later known as Korean lespedeza, was first tested in 1921 at the Arlington Experiment Farm, Arlington, Virginia, where it was found to be a vigorous, early-maturing species. It was further tested by agricultural experiment stations and was found to be well adapted across the upper part of the lespedeza region.

By 1935 the widespread acceptance of Kobe and Korean lespedezas had raised the crop to a major status in the southeastern states.

Lespedeza was first known as Japan clover in the United States. Later the name "lespedeza" became common. As seed of Kobe became available, the older seed stock of *L. striata* became known as common lespedeza. Common lespedeza, a branching, lower growing type than Kobe, is now recognized by farmers and seedsmen as a variety of *L. striata*. These and other varieties of *L. striata* make up the striate group. In the same manner, the varieties of *L. stipulacea* are known as the Korean lespedezas.

The perennial lespedeza, *L. cuneata*, was first introduced in 1896 under the name *L. sericea* but did not appear particularly promising in preliminary studies in North Carolina (McCarthy, 1896). A second introduction in 1899 was grown at the Arlington Experiment Farm, and seed was distributed to a farmer in Tennessee, where it became established over a considerable area in Overton County (Mooers, 1938). The Virginia planting became well established, and long after the original planting was discontinued, plants of *L. cuneata* continued to volunteer in waste areas on the experimental farm. Additional introductions of various perennial lespedeza species were received from Japan in 1924 by the Bureau of Plant Industry of the U.S. Department of Agriculture. These introductions have been evaluated with the earlier introductions in the cooperative programs that the United States Department of Agriculture carries on with state agricultural experiment stations.

4. *Seed Characteristics*

The fact that lespedeza seed can be produced easily and in relatively large quantities in its area of adaptation is one of the reasons for the popularity of this crop among farmers. Seed of the annual species is usually marketed and sown in the hull. Most of the sericea seed is hulled, but both hulled and unhulled seed are usually available.

Seeds of the economic species of lespedeza differ and are easily distinguishable. The calyx continues to cling to the pods of cleaned seed of unhulled annual species but can rarely be found on sericea seed. Hulled seeds of the annuals are blue-black and may or may not be mottled. In contrast sericea seeds are greenish yellow and faintly mottled (Fig. 2). The calyx surrounds the pods of common lespedeza, with

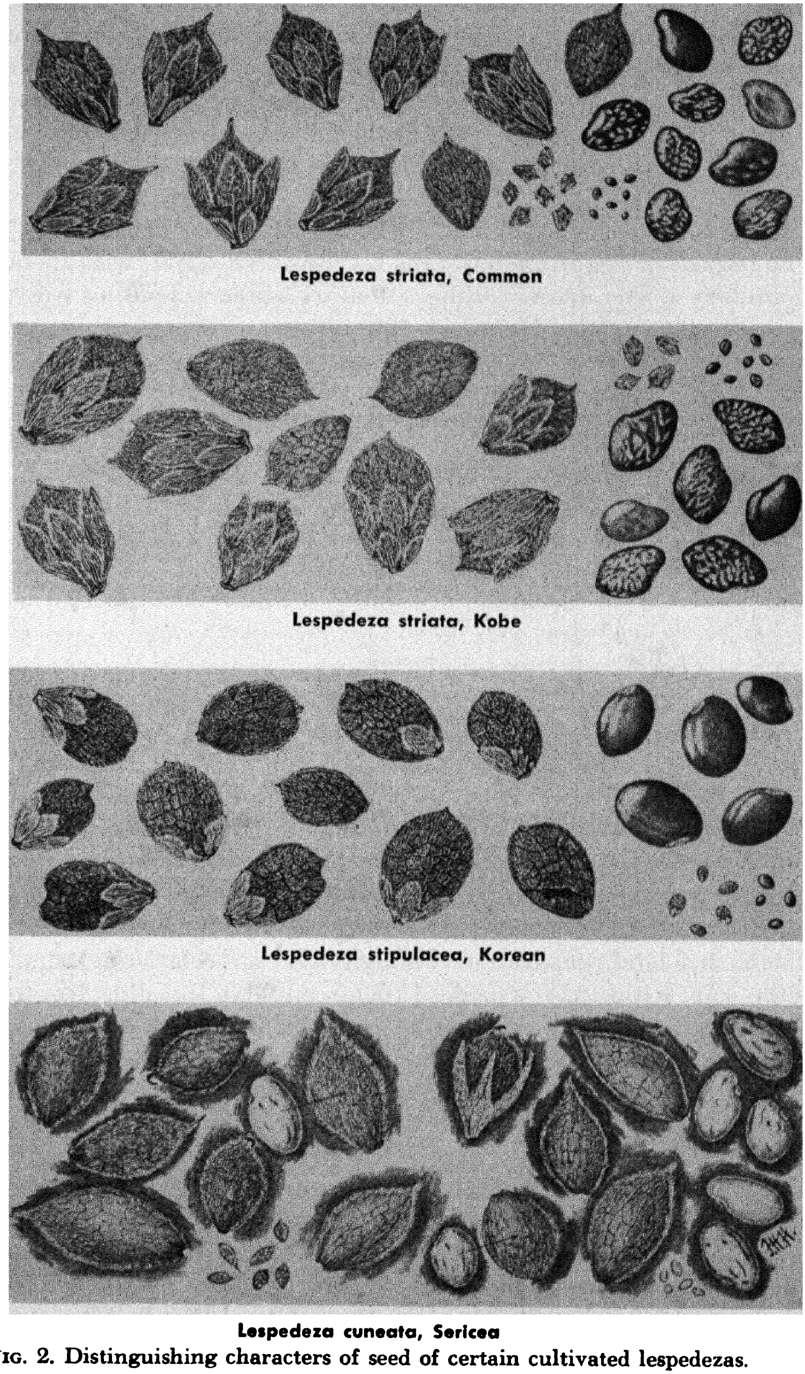

FIG. 2. Distinguishing characters of seed of certain cultivated lespedezas.

the lobes bluntly pointed and almost as long as the pod. The pods of Kobe resemble those of common lespedeza except that they are decidedly larger and less sharply pointed. The pods of Korean are more rounded, blunt, and strongly reticulated, with calyx lobes approximately one-fourth the length of the pod. Hulled Korean seeds are blue-black, whereas striate lespedeza seeds usually have some mottling.

5. *Distribution and Acreage*

The lespedeza region includes the southeastern states, with its northern boundary a line across southern Pennsylvania extending westward to the southeastern tip of Nebraska (Fig. 3).

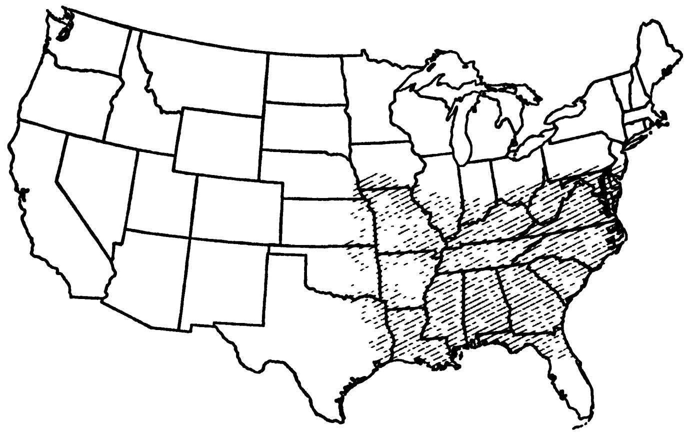

FIG. 3. The lespedeza region of the United States.

The lespedezas do not compete with alfalfa and the clovers for land area. Instead, their principal field of use begins on soils on which alfalfa and clovers cannot be grown without excessive expenditures for lime, fertilizers, and land preparation. Though there are relatively large areas of fertile soils within the lespedeza region suitable for other legumes, a major portion of the soils of the area are low in fertility and frequently badly eroded. However, on extremely acid, infertile soils lime and fertilizer are needed for satisfactory lespedeza production. Estimated acreage figures are available for only that portion of the acreage harvested for seed and for hay. The acreage of the striate lespedezas harvested for seed and hay had leveled off by 1925 to around 300,000 acres (U.S. Dept. Agr., 1938). The release of Kobe and particularly Korean lespedezas in the late 1920's served to renew, and within a short period of time, greatly to expand the acreage.

The average acreage of lespedeza for seed and hay by five-year periods beginning in 1926 is given in Table I (U.S. Dept. of Agr., 1938–

TABLE I

Average Lespedeza Acreage and Yield of Seed and Hay by Five-Year Intervals, 1926–1955

	Seed		Hay		Total acres for seed & hay (thousands)
	Acres	Pounds (thousands)	Acres	Tons	
1926–1930	41,680	4,429	350,600	363,800	392
1931–1935	251,300	42,415	1,254,200	1,268,200	1,505
1936–1940	570,420	104,125	3,415,200	3,546,400	3,986
1941–1945	903,260	164,572	6,360,600	6,589,800	7,264
1946–1950	897,660	184,930	6,607,000	7,261,200	7,505
1951–1955	652,160	122,294	5,036,200	4,922,200	5,688

55). It should be noted that a fourfold increase in acreage occurred during 1931–35 as compared to the period 1926–30, when little or no Korean was grown. The total acreage doubled during the next five years (1936–40) and doubled again from 1941 to 1945. This rapid increase in the total lespedeza acreage was due primarily to the expanding use of Korean. Korean fitted well into grain crop rotations across the upper half of the lespedeza region and filled the need for a productive pasture legume for midsummer to early fall grazing.

Little Korean lespedeza seed was produced in 1928–29, but in 1938 83.2 per cent or 149 million pounds of the total lespedeza seed crop was of the Korean variety (U.S. Dept. of Agr., 1938). During this same period, the acreage of Kobe lespedeza was also increasing but less rapidly. Approximately 12 per cent of the total, or 21 million pounds of Kobe seed, was produced in 1938.

The seed production by species and varieties by five-year intervals for the period 1941–55 is given in Table II.

TABLE II

Average Total Lespedeza Seed Production in Pounds by Five-Year Periods, 1941–1955[1]

Variety	1941–45 (thousands)	1946–50 (thousands)	1951–55 (thousands)
Korean	133,468	136,108	84,872
Kobe	22,876	36,801	27,883
Common	4,773	3,329	1,468
Sericea	3,456	8,692	8,071

[1] Averages calculated from annual lespedeza seed forecasts, Crop Reporting Board, A.M.S., U.S.D.A.

The low seed yields of Korean and Kobe lespedeza for the five-year period 1951–55 is due largely to drought damage during 1953 and 1954, particularly in Missouri, where the acreage harvested and the yield per acre were much lower than usual. However, during the period 1951–55 there was a tendency for growers to increase the amount of nitrogen fertilizer applied to small grains to provide more early spring grazing or to increase grain yields, or both. The increased growth of the small grains frequently smothers many lespedeza seedlings, resulting in thin, unproductive stands. The seed production totals for sericea lespedeza indicate increasing interest in this perennial species for forage and soil improvement.

The acreage of lespedeza harvested for hay and seed is a relatively small part of the total lespedeza acreage. This is due in part to the fact that a large acreage of lespedeza is grazed or turned under for soil improvement. Much of the lespedeza acreage is either in mixtures with grasses as permanent pastures or meadows where it may or may not be grazed and in one- and two-year rotations with small grain where it is grazed or turned under for soil improvement. In any case, the acreage is not reported as lespedeza. The total lespedeza acreage in Missouri was estimated at 10 million acres (Etheridge *et al.*, 1954), of which only 1.4 million or 14 per cent was harvested for seed and hay. In Indiana (Beeson, 1941) the 82,000 acres harvested was 16 per cent of the total estimated acreage. In Kentucky, the 502,000 average acreage harvested for hay and seed for the two years 1935–36 (U.S. Dept. Agr., 1936) is 17 per cent of the 3 million estimated total acreage (Kinney *et al.*, 1937). These and other unpublished reports indicate a correlation between the total acreage and the acreage of lespedeza harvested for seed and hay, with the latter being approximately 20 per cent of the total acreage. From estimates based on acreages harvested for seed and hay, the total acreage of lespedeza in the region varies from a high of 50 million acres in 1949 to an average of about 30 million for the period 1951–55.

II. Culture and Utilization[1]

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1. Introduction

Within their region of adaptation, annual lespedezas are grown on a vast scale. Few crops return such immediate profits. They are easily

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and cheaply established, reseed dependably, and are relatively tolerant of drought and pests; they produce nutritious, nonbloating, easily cured forage at the season of greatest pasture need and at the season when convenience and curing weather make haymaking easiest. They tolerate low fertility, yet respond to soil treatment, and contribute to soil improvement. They are remarkably versatile, being suited to most soils, to most grass companions, for use in permanent pastures for hay or seed, and in rotations of any length. They are good feed for all kinds of livestock.

These characteristics have made the crop important and assure its continued, widespread use despite increasing emphasis on other crops with higher yield potentials under heavy fertilization and careful management.

It is recognized that agriculture's return to more prosperous conditions during and following World War II enabled farmers to make heavy investments in soil treatments, and resulted in the shifting of some lespedeza acreage to other higher yielding legumes. It is reasonable to expect this trend to continue, depending upon the general prosperity of agriculture.

Sericea lespedeza has not attained the importance of annual lespedezas. Though tolerant of drought and low fertility, and capable of outyielding and improving soil more rapidly than the annual lespedezas under favorable management, it lacks their feeding quality, ease of production, and range of use. However, improved varieties and production practices developed by research may greatly extend its use.

The subject of the culture and utilization of lespedezas is vast and its literature voluminous. Because of space limitation the discussion will be relatively brief and general.

2. Cropping Systems

An outstanding feature of annual lespedezas is the ease with which they fit into various cropping systems (Etheridge and Helm, 1936; McKee, 1940). Since lespedeza mixes well with most grasses and thrives in small grains, furnishing pasture, hay, or seed after the grain crop is harvested and then reseeding itself the next year, it can be used in almost any kind of rotation. Few if any changes need to be made in the crop sequence when lespedeza is added. It fits readily into flexible short rotations which facilitate the cropping of farms having variable soil and topography and which adapt quickly to changes in weather and prices. It fits just as readily into long rotations that include small grain or several years of grass-legume sod.

Lespedeza usually is established in small grain either as a pure stand or in mixture with grasses and other legumes. After one or more years, the lespedeza is followed by a row crop such as corn, soybeans,

tobacco, or cotton. If small grain is omitted from the system, lespedeza usually follows a row crop and may occupy the land from one to several years.

Double cropping with small grain and lespedeza is an old practice (McNair and Mercier, 1911; Butler, 1917) that increased in popularity after the introduction of Korean lespedeza (Duncan, 1955). The small grain-lespedeza combinations have been studied intensively and widely used in Missouri (Etheridge and Helm, 1936; Helm, 1936; Burch, 1940; Brown, 1953; Etheridge *et al.*, 1954). The small grain is harvested as pasture, hay, silage, or grain, and is followed by lespedeza which comes on in the stubble and produces pasture, hay, or seed. Any of the small grains may be used, and the one-year rotation can be continued indefinitely (Helm, 1940).

Sericea is more difficult to use in rotations than annual lespedeza. It is hard to establish in small grains, is somewhat uncertain in summer seedings following small grains, and in either case may require more than one season to become fully established, thereby taking the land out of production. Omitting the small grain to improve the establishment of sericea takes the land out of production for one season. Aside from these limitations sericea is a desirable legume in rotations on many soils because of its productiveness and its soil-conserving and soil-improving qualities (Pieters *et al.*, 1950; Bailey, 1951). Two or more years of sericea are followed by one or more years of cultivated crops such as corn or cotton, and then by a crop of small grain. In some cases the cultivated crop is omitted.

3. *Soil Requirements*

The annual lespedezas will thrive on most soil types but there are some limits. They usually do not thrive on wet or alkaline (high-lime) soils, or on sandy soils that are droughty or nematode-infested; their production is not satisfactory on extremely acid soils and infertile without corrective treatments. Yields are best, of course, on deep, fertile, well-drained soils that retain moisture.

Sericea has similar requirements but seems to be somewhat better adapted than annual lespedezas to high-lime soils and to sandy soils (Bailey, 1951). Stephens (1952) states it does not grow very well on sandy or poorly drained soils of the lower Coastal Plain.

Lespedezas perform best on acid soils within the approximate range of pH 5.8 to 6.3 (Giddens, 1954). At values of about pH 5.0 or below, depending on the specific soil, manganese toxicity appears in annual lespedezas (Morris. 1948). Other harmful factors often associated with low acidity include an inadequate supply of soil nutrients, poor nodulation, and excessive concentrations of soluble iron or aluminum.

When the pH rises above 6.5, depending on the specific soil, the growth of lespedeza is depressed. This unfavorable effect of high base saturation or of overliming is believed to be related to the reduced availability of phosphorus, iron, manganese, and other minor elements at higher pH levels (Paden, 1953; Giddens, 1954). Marshall (1944) believed that in his experiment manganese shortage was the limiting factor.

In soils or nutrient solutions which are alkaline, lespedeza frequently becomes chlorotic and dies in early stages of growth (Morris and Pierre, 1947; Hughes, 1949). The chlorosis apparently is caused by a deficiency of iron in the plant.

Many investigators have reported that Korean lespedeza is less tolerant of soil acidity, more tolerant of alkalinity, and more responsive to liming than varieties of *L. striata*, including Kobe. It is interesting to observe in the data of Weathers (1938) that a high content of manganese is a characteristic of Kobe. A strain of Korean (IOWA 39) has been developed which will grow on soils of pH 8.0 or above (Hughes, 1949).

4. Soil Treatment

Many states now recommend that initial treatments be made to eliminate soil deficiencies as determined by soil tests. Liming to pH 6.0 or 6.5 probably is satisfactory under field practice, although temporary overliming effects may be noted on certain soils at the higher pH. Maintenance applications of phosphorus and potassium should be made to replace removal in the crop and by animals, and to correct for the uneven distribution of nutrients returned in the excreta of grazing animals (Peterson *et al.*, 1956). For pastures, the equivalent of 20 or 30 pounds P_2O_5 per acre per year is recommended and may be applied annually, or less often in larger amounts.

If the grower is unable to make heavy initial applications, smaller amounts may be used, and the treatments repeated at frequent intervals. This is a very economical and practicable method of bringing poor land into good production with the use of lespedeza-based mixtures (Hutcheson, 1941; Etheridge, 1946).

a. Annual Lespedeza in Pure Stands. Data from 34 tests in eight states have been assembled in Table III to show the generalized response of lespedezas to soil treatment.

Limited data indicate that seed yields are influenced by soil treatment in about the same manner as hay yields.

Either limestone or phosphate considerably increases the yield, although on extremely poor soils one without the other may fail to give a response (Hutcheson, 1941; Woodhouse and Lovvorn, 1942).

Potassium usually gives a marked response after the soil has been limed and phosphated and the subsequently increased growth of the

TABLE III

The Response of Annual Lespedezas to Soil Treatments

Treatment	Hay yield (lb./acre)	Relative yield
None	1558	100
Limestone	2588	166
Phosphate	2096	135
Potash	1764	113
Limestone and phosphate	3034	195
Limestone, phosphate, and potash	3614	232

lespedeza or its preceding crop has depleted the available soil potassium.

According to various reports, rock phosphate is a satisfactory source of phosphorus for lespedeza in Illinois, Missouri, Arkansas, and Kentucky. A recent report (Gill, 1956) from the Brown Loam Branch Station in Mississippi stated that rock phosphate at a heavy initial rate was as productive as 60 pounds annually of phosphate from soluble sources when used for Dallis grass and lespedeza forage production.

Other findings of interest from the literature are as follows: The response of lespedeza to lime and fertilizer may increase greatly after the legume has occupied the land long enough to deplete the available soil nutrients; if lespedeza follows well-fertilized crops and occupies the land only one year, fertilizers are seldom needed; only a small response to nitrogen fertilizer is obtained if the soil is well supplied with calcium, phosphorus, and potassium; the placement of calcium, phosphorus, and potassium for lespedeza is of relatively small importance, and surface applications by broadcasting, drilling, or disking are very effective.

Deficiency symptoms of phosphorus and potassium in lespedeza have been described (Blaser *et al.*, 1943). Potassium-deficient plants were dwarfed and exhibited leaves that were mottled, chlorotic or greenish-yellow, and often burned or browned, starting from the tips. Phosphorus-deficient plants were dwarfed and exhibited light yellow leaves with purple margins, mid-veins, and petioles. The deficiency symptoms of each element varied somewhat depending on the relative abundance in the soil of the other nutrient elements. For example, with abundant calcium and potassium, phosphorus-deficient plants were dwarfed and exhibited leaves colored dull, dark green, or purple and purplish-green, with purple leaf margins, mid-veins, and stems. Normal leaves are light green with white mid-veins. Stitt (1939) described the seedling growth on a very poor soil as follows: "During both seasons the lespedeza plants grew to about 1 to 2 inches high, became yellowish in color with red leaf margins and stems, after which most of them

died." Blaser *et al.* (1943), concluded that Stitt probably was describing phosphorus deficiency in his plants.

Iron deficiency in lespedeza is characterized by a general yellowing of the leaves and by stunted growth. Manganese toxicity, if mild, may resemble iron deficiency; when severe, the symptoms are yellowing and crimping of the leaf margins, with some of the older leaves becoming completely yellow and speckled with small brown spots between the veins. The above are described by Morris and Pierre (1947), and Morris (1948).

Boron deficiency apparently occurs rarely in lespedezas, but if induced it is expressed by reddish-purple discolorations of the leaf margins (DeTurk, 1941).

The mineral composition of lespedeza in pure stands varies considerably, depending upon soil fertility, soil treatment, location, season, stage of growth, and other factors. Space limitation permits only a brief discussion of this topic, on which much information is available.

Lespedeza hays from fertile soils usually are higher in nitrogen, phosphorus, calcium, and ash than those from infertile soils. Similar variations result from differences in soil treatment. A summarization of 18 tests in several states shows that the addition of lime, phosphate, and potash to untreated soil increased the nitrogen, phosphorus, and calcium contents of the plant 23, 27, and 21 per cent, respectively. Fewer analyses were available for the other constituents. The content of total ash increased 32 per cent, and that of potassium, which was quite variable, increased 8 per cent. The content of manganese and silicon declined sharply, whereas that of magnesium was variable. The addition of lime and phosphate nearly always increased the content of nitrogen, calcium, and phosphorus. The addition of phosphate only to infertile soils nearly always increased the content of nitrogen and phosphorus and usually that of calcium; the addition of lime only nearly always increased the content of nitrogen and calcium and often increased that of phosphorus. There is a strong tendency for high nitrogen to occur with high phosphorus, and a lesser tendency for high nitrogen to occur with high calcium concentration in the plant.

In comparing Korean with certain other plants, Marshall (1944) commented that this legume was chemically remarkable in several ways, particularly in that it was very low in sodium, low in potassium, and did not attain "luxury" levels of consumption, and in that it maintained a greater constancy of base ratios than the other plants. Paden and Garman (1946) found that Kobe exhibited low sodium content and a certain constancy of base ratios.

Annual lespedezas in most cases are lower in calcium, phosphorus, and potassium than legumes with more exacting soil requirements.

They deliver more total digestible nutrients with a unit of mineral than most of the exacting legumes, being especially conservative in the use of potassium.

Buckner and Henry (1945) showed that Korean clipped frequently was higher in calcium and phosphorus than Korean allowed to grow for hay during the same period, but produced only 39 per cent as much dry matter and removed only 53 per cent as much calcium and phosphorus from the soil.

From among the many references which describe the mineral content of lespedeza, the following may be consulted for additional details: Weathers (1938), Beeson (1941), Price *et al.* (1946), Snider (1946), Morris (1948), Morrison (1950), Haigh (1952), Cloninger and Herman (1953), Pickett (1955), and Price *et al.* (1955).

b. Annual Lespedeza in Mixed Stands. The response to soil treatment of lespedezas grown in mixed stands requires separate discussion. In mixed stands the lespedeza is under competitive pressure from associated species, and soil treatment may benefit the associated species to the detriment of the lespedeza. Thus species interactions add an element of uncertainty to the response.

Lespedeza grown with small grain usually benefits from liming, but the application of fertilizers, particularly those containing nitrogen, may greatly depress lespedeza yields owing to increased competition from the invigorated grain crop. Early removal of the grain crop as pasture, hay, or silage, or widening the grain rows may lessen the competition.

In mixtures of grasses and lespedeza, high fertility levels stimulate the grasses and encourage volunteer clovers, resulting in increased competition which depresses the lespedeza. For the Cotton Belt, Thompson (1954) recommends spring rather than fall application of fertilizers to avoid excessive stimulation of clovers. Managed grazing and the use of bunch-type grasses and limited amounts of fertilizer also help in the maintenance of lespedeza.

Great caution should be exercised in the use of nitrogen. In Missouri tests, the results of which have not been published, 66 pounds of nitrogen applied in early spring to bluegrass quickly eliminated Korean. During a seven-year period the nitrate-treated bluegrass pasture averaged 309 pounds per acre of beef and 1.78 pounds daily gain; the check pasture of bluegrass-lespedeza averaged 201 pounds per acre and 2.02 pounds daily gain. The carrying capacity was much better distributed through the season in the bluegrass-lespedeza pasture. Lespedeza should not be driven out of cool-season grasses with nitrogen unless extra supplementary summer pasture can be economically provided to balance the heavy spring capacity of the nitrogen-stimulated grass.

Although the majority of studies show that the use of nitrogen for mixtures harms the lespedeza, such use is recommended by a few writers.

c. Sericea Lespedeza. Relatively few data are available on the effect of soil treatment on growth and chemical composition of sericea. From available data it seems that the general relationships which hold for the annual lespedezas also hold for sericea.

On better soils, response to lime and fertilizer is often small. On poorer soils, lime should be added for a pH of 5.8 or 6.3, and phosphate should be supplied. Potash generally is needed after phosphate has been added.

If sericea is grown in mixtures, potash should be applied in amounts sufficient for the needs of all species included, otherwise the associated species may dominate in the uptake of potassium and the sericea be weakened.

Limited data indicate that the mineral composition of sericea varies with soil treatment and soil type in much the same manner as that of the annual lespedezas.

5. *Lespedeza as Feed*

Garrigus (1954) points out that the first limitation of pasture as feed for fattening younger animals or for milk production is inadequate intake of digestible nutrients. This may be due to unpalatability, low dry matter content, or indigestibility of dry matter.

McCullough (1953, 1956) describes a high-quality forage for milk production as one meeting the following specifications:

a. Dry matter digestibility—70 per cent or more.
b. Crude protein—16 to 20 per cent.
c. Crude fiber—not over 25 per cent.
d. Intake—3.5 pounds of dry matter per 100 pounds of body weight.

These descriptions forcefully emphasize the importance of digestibility and net energy intake in forage quality. They do not minimize the importance of minerals and carotene. Such forage is not often deficient in these constituents. Toxic levels of various substances, bloat-producing factors, milk-stimulating factors, and other miscellaneous factors must also be considered.

a. Annual Lespedeza Hay. The value of lespedeza forage has varied widely in feeding and grazing experiments. This is to be expected because hay of the same kind varies widely in quality owing to stage of maturity, curing and handling, soil and weather conditions, and other factors that influence leafiness and composition. Any pasture herbage of the same kind varies in similar fashion. It is extremely difficult to eliminate all variables except species differences. Properly compared, lespedeza hay cut in early bloom or before and preserved without ex-

cessive losses is equal to or approaches good alfalfa hay in feeding value (Morrison, 1950). Any differences usually are closely related to content of total digestible nutrients.

Good lespedeza in comparison with good alfalfa hay is leafier and higher in carotene, but lower in digestible nutrients, especially digestible protein, probably owing to higher lignin content, especially in the leaves. It is lower in calcium, potassium, phosphorus, sodium, chlorine, and boron, and higher in manganese, with other elements inconsistent. The riboflavin in lespedeza, in contrast to that in alfalfa, is available to poultry.

The most significant factor in the quality of lespedeza hay is digestibility (Swanson and Herman, 1943, 1944; Rusoff *et al.*, 1946; Morrison, 1950; McCullough *et al.*, 1953). As the crop matures it becomes highly lignified, low in digestibility and total digestible nutrients, but it retains considerable feeding value if it carries a good percentage of seed.

Muhrer and Gentry (1948) reported prothrombin deficiency and hemorrhage in livestock and rabbits eating moldy lespedeza hay. Unpublished work in Ohio indicates that toxic dicoumarin is present in stack-heated, tobacco-cured, or moldy hay. Clinical files show that such hay is a source of trouble in Missouri, where it is considered good practice to perform clotting tests on herds which are to be dehorned or castrated, if they have been on lespedeza hay of questionable quality.

b. Annual Lespedeza Pasture. Annual lespedezas are most productive and most dependable when grown in pure stands free from competition with other plants. However, weeds encroach rapidly in pure stands and cause a decline in productivity and usefulness. Furthermore, the lespedezas do not make full-season use of the land. For these reasons the crop usually follows small grain or is grown in a mixture with grasses in permanent or rotation pastures. It also may be included in grass meadows where it furnishes summer pasture following an early cutting of grass hay.

(1) Following small grains. Lespedeza following small grain is productive, providing the grain crop has not been unusually competitive, and moisture conditions have been favorable during the summer. Fertilizing the small grain heavily, using late-maturing grains, and removing the crop late as grain, are practices which cause the lespedeza to be thin in stand, slow to develop, and low in yield. By using moderate rates of fertilizer application and early-maturing grains, or by grazing the small grain, the lespedeza crop which follows is palatable and nutritious and highly valued for fattening cattle. Dyer (1952) compared fescue-ladino with wheat-lespedeza for pasturing steers. The fescue-ladino, containing over 50 per cent legumes, had 150 per cent larger carrying capacity. The wheat-lespedeza steers gained 42 per cent faster on pas-

ture, required only 42 per cent as much corn to finish, made 29 per cent more of their gain from forage, and reached market 49 days sooner than the fescue-ladino steers. Numerous cases of bloat occurred on the ladino.

Many data on Korean lespedeza pastures, few of which have been published, are available at the Missouri Experiment Station. Examination of these data shows that production has varied from total failure to extremely high yields. Most of the variation is associated directly or indirectly with weather conditions, although other factors such as variations in soil, grazing management, and kind of cattle used also have influenced the results.

Lespedeza following winter wheat harvested for grain usually has produced 100 pounds per acre of beef in the period July 16 to September 16. The highest yield obtained under normal conditions was 217 pounds. The high rate of gain of steers on lespedeza in summer, often averaging 2.0 pounds daily, is probably due to the combination of low water content and high palatability which favors high intake, satisfactory levels of digestibility and protein, and freedom from bloating and scouring.

It has been observed in Missouri that cattle continue to gain well on lespedeza until the seeds form and mature, when they usually cease to gain but hold their finish. Steers on Korean in this stage, September 29 to October 13, gained 1.28 pounds daily and were then moved to a mixture of grass and lespedeza until December 1, gaining 1.34 pounds daily (Dyer, 1952). Hutcheson (1941) maintained cattle in excellent condition from October 15 to December 20 on mature lespedeza. The seeds of lespedeza are digested to a certain extent, depending on hardness (Burton and Andrews, 1948), and are an excellent source of protein for animals (Swanson and Herman, 1944; Ackerson and Mussehl, 1954). Yields of lespedeza have usually been high when summer moisture was abundant or when something happened that weakened the grain crop without hurting the lespedeza. In 1941 after the wheat had winterkilled severely, grazing started June 15, a month earlier than usual, and lespedeza produced an average of 233 pounds per acre at four locations (one location produced 355 pounds).

The yield of lespedeza following spring oats has been less, whereas the yield following winter barley has been greater than that following wheat. Lespedeza following spring oats harvested for hay has outyielded considerably that following oats for grain. Early removal of a small grain by harvesting it as hay or silage usually improves the performance of lespedeza, but in certain seasons the grain crop will damage the legume severely before the date of hay harvest.

Dairymen in Missouri have long complained of the poor quality of

lespedeza pasture in late summer after the plants come into bloom, fully a month before the quality drops for fattening animals. They report that the milk flow falls off and that the cows tend to fatten. Tannin was blamed for lessening milk flow. After investigating the problem, Herman *et al.* (1953), concluded that reduced milk flow probably was due to lack of available nutrients as the plants matured rather than to high tannin.

An allergy or disease called mycotic stomatitis has been associated with lespedeza pastures in Missouri (Ebert, 1953) and in other states. Occasional light outbreaks occur in August or September, and in most cases the affected animals have been grazing lespedeza or lespedeza in mixtures.

An important fact obtained from the Missouri data is the high yield of the winter wheat and lespedeza combination if both are utilized as pasture. This combination over a period of years has given an average yield of 285 pounds of beef per acre, an average daily gain by steers of about 1.7 pounds, and a period of use extending from April 20 to September 25. The highest average yield at one location was 365 pounds, and the highest yield in one year at a single location was 439 pounds. The earliest grazing obtained in any one year was March 30, and the latest October 21. The gain on wheat has comprised as much as 70 per cent and as little as 20 per cent of the annual yield but usually about 50 per cent.

Rye and lespedeza pasture furnishes earlier grazing than wheat and lespedeza, but gives a lower yield and a wider gap between the small grain and lespedeza. The average yield of this combination at one location in Missouri was 221 pounds per acre of beef, and the highest 290 pounds. Spring oats and lespedeza pasture was relatively low-yielding, chiefly because of the poor yield of oats under grazing. Winter oats are used with lespedeza in the Cotton Belt, and this combination has yielded 209 pounds per acre of beef (Skelton, 1945). The oats was grazed on the average from February 3 to May 6 and yielded 107 pounds of beef; the lespedeza was grazed from June 18 to October 21 and yielded 102 pounds of beef.

(2) *Combinations with grass.* The annual lespedezas occupy millions of acres in mixtures with grasses for pasture. Lespedeza-grass mixtures have many desirable features. They are easily and cheaply established and maintained, relatively persistent, and nutritious. Growth is fairly uniformly distributed through the growing season. Lespedeza is the easiest of all legumes to introduce into established sods, and is therefore a logical choice of species to sow in grass after stands of ladino clover or alfalfa have thinned or disappeared.

It is known that lespedeza improves the productivity of grass pas-

tures by adding its own nutritious herbage and by furnishing extra nitrogen for the grass. The extra gain obtained from steers by adding lespedeza to bluegrass amounted to 55 pounds per acre, an increase of 55 per cent (Brown and Helm, 1945). Adding lespedeza to carpet grass increased the yield by 28 pounds of beef (Blaser *et al.*, 1943). Lovvorn (1944) in some cases doubled herbage production by adding lespedeza to Dallis grass, Bermuda grass, or carpet grass. Woodhouse and Lovvorn (1942) doubled the yield of Dallis grass during April, a month when forage is badly needed, by adding lespedeza. The increased growth was due to the effect of the legume on the grass, since lespedeza did not contribute directly to the yield during that month. Roberts and Olson (1942), Baldridge (1946), and Peevy (1953) all found that lespedeza increased considerably the yields of associated grasses.

Lespedeza thrives with some grass species better than with others. In general it associates best with bunch grasses, such as timothy, orchard grass, or Dallis grass; but in many cases the vigor of the grass and its management have more to do with the success of the legume than the species. In dense, vigorous stands it is important to keep the grass grazed down to prevent smothering of the lespedeza. Even then, occasional resowing of the lespedeza, accompanied by sod tillage, may be necessary to maintain the legume in Bermuda grass (Stephens, 1952). Overgrazing the mixture in the fall may prevent lespedeza from producing enough seed for reseeding.

The presence of volunteer clovers greatly increases the difficulty of maintaining lespedeza in grasses. Although grasses usually are stronger competitors than lespedeza, the legume occasionally may injure the associated grass. This usually happens when a good stand of lespedeza, favored in summer by abundant moisture and undergrazing, becomes rank. Although lespedeza at times may weaken the grass during the summer (Lovvorn, 1944), this effect generally is more than offset by the benefits of nitrogen added by the legume.

Korean lespedeza has been grown with most of the cool-season grasses by workers at the Missouri Experiment Station. The average yield over many years of the various mixtures of grass and lespedeza has been 196 pounds of beef per acre. The highest yield in one year was 297 pounds per acre, obtained from orchard grass and lespedeza. The average yield of the various grass-alfalfa or grass-ladino mixtures grown at relatively high soil fertility levels was 312 pounds per acre, and the highest yield in one year, 516 pounds, was obtained from tall fescue and ladino. The average yield of wheat and lespedeza (both pastured) was 285 pounds, and the highest 439 pounds.

Blaser *et al.* (1956) obtained yields of 268 pounds per acre of beef from orchard grass-lespedeza-white clover and 333 pounds from grass-

ladino. Burger *et al.* (1952) obtained yields of 220 pounds per acre of beef from tall fescue-lespedeza, 318 from orchard grass-lespedeza, and 425 from grass-ladino.

Lespedeza produces abundantly following the harvesting of early hay from cool-season grasses. Cattle gains of 50 to 100 pounds or more per acre can be expected from this system of utilization. Timothy or orchard grass do well in mixtures used in this manner.

In the lower South, the average yield of mixtures of warm-season grasses and lespedeza as determined for locations in several states amounted to 204 pounds of beef per acre. The yield of grass-clover mixtures adequately fertilized was 352 pounds of beef per acre.

It is of interest that Dr. Ralph Mills, the discoverer of Korean lespedeza, found *Lespedeza striata* growing with *Zoysia pungens,* a warm-season grass, forming a natural grassland association in northern Korea and Manchuria (Mills, 1921).

c. Sericea Hay and Pasture. The feeding value of sericea is a controversial subject, and much additional research is needed to reconcile differences of opinion. Obviously, sericea roughages have not been tested thoroughly for quality at all stages of growth, under wide differences in soil fertility, by all classes of livestock, and in various rations.

Bailey (1951) believed that vigorously growing sericea cut or grazed in young, tender stages of growth is excellent feed for livestock. The results of the limited number of feeding and grazing trials have ranged from good to poor, with the poor predominating. As Hawkins (1955) and others have pointed out, the experimental findings may be summarized as follows:

1. Sericea in most cases has not been very palatable.

2. Daily gain or milk production has tended to be low; however, in a few tests the crop has been 80 or 90 per cent as valuable for feed as the more highly regarded legumes.

3. It has been assumed generally that high tannin content is a major factor in low consumption.

4. Evidence is accumulating that low digestibility is a major factor limiting the quality of this forage.

In fairness to sericea it must be said that in relatively few instances has the experimental forage been of the high grade needed to produce excellent results. However, even under circumstances where the crop should have given excellent results, it has not always done so. Although it is doubtful that sericea will ever equal the better legumes as feed for animals having a high requirement for intake of digestible nutrients, the crop still may be an economical source of forage for such animals on many farms, and it may be entirely satisfactory as feed for animals with lower requirements.

The many instances of poor performance of animals feeding on sericea appear to have been a natural consequence of low nutrient intake because of low palatability and low digestibility.

The cause of low palatability is uncertain. The tendency of the plant to become coarse and woody is one explanation, and the high content of tannin is another (Pieters *et al.*, 1950; Wilkins *et al.*, 1953; Donnelly, 1954). The results of rationed feeding of tannin throw doubt on the significance of this substance in determining palatability (Herman *et al.*, 1953; Hawkins, 1955), although it is not certain that the feeding of tannin in rations duplicates the natural condition in the plant (Clarke and Cotchin, 1956).

The low digestibility of sericea (Holdaway *et al.*, 1936; Morrison, 1950; McCullough *et al.*, 1953) probably is related to high lignin rather than to high tannin content (Hawkins, 1955). One interesting fact reported by Hawkins is that the apparent lignin content of sericea was reduced from 25.47 to 13.97 per cent by extraction of tannin from the sample and correction for crude protein. Most of the reduction was associated with correction for crude protein.

Stephens (1952) reported that sericea grazed from April 29 to November 6 produced on the average 91 pounds per acre of beef. Common lespedeza grazed from June 20 to October 9 produced 88 pounds per acre of beef. Pieters *et al.* (1950) cited grazing trials in which cattle produced as much as 357 or 417 pounds per acre on sericea, but at a low rate of gain.

Sericea usually is grown in pure stands for pasture. Pieters *et al.* (1950) and Bailey (1951) emphasized the importance of grazing the plants when less than 6 inches high, and recommended clipping if necessary to keep the growth short and tender. If it is necessary to graze a field after the plants are large enough to make hay, then the crop may be mowed and windrowed for the cattle to eat until the new growth appears.

The necessity of keeping sericea grazed closely or clipped in order to render it palatable and nutritious has certain disadvantages. The stands may be short-lived under this management, especially if grazing is continued for the entire season and if winter heaving is severe or the soil is infertile. It is difficult to maintain a reasonable reserve of herbage for periods of reduced growth, and frequent defoliation reduces the yield of herbage.

There has been considerable interest in growing cool-season plants with sericea in order to extend the season of use. Small grains, crimson clover, and other winter annuals can be established in short growths of sericea during the fall. They grow abundantly if soil fertility levels are adequate for their needs, but tend to weaken the sericea in the spring even under good grazing management.

Cool-season and also warm-season perennial grasses tend to crowd out sericea under grazing or frequent mowing. If considerable growth of sericea is allowed to develop and make seed, the legume is favored in the competition, but the forage possibilities of the mixture then are restricted.

Despite the difficulties attending its utilization, sericea has a place on land where other crops which are considered superior to it will not grow dependably or will not grow without prohibitive expense.

d. Mineral Levels. Because lespedezas are grown on infertile soils it has been feared that the forage might be deficient in minerals for livestock (Fergus, 1936). As mentioned earlier, many data are now available on mineral content of annual lespedezas. Assuming that phosphorus levels below 0.13 per cent and cobalt below 0.07 p.p.m. in the dry ration are suboptimum for cattle and sheep (Pfander, 1955), it appears that these two elements may drop to inadequate levels in forage because of soil or other factors. As an example, surveys made by Cloninger and Herman (1953) and Pickett (1955) revealed that 12 per cent of the Korean samples were inadequate in phosphorus, as low as 0.09 per cent in content, and 12 per cent of the samples were inadequate in cobalt, as low as 0.02 p.p.m.

Limited data indicate that the phosphorus content of sericea grown on extremely poor soil may approach inadequacy for livestock. However, this crop tends to be higher in phosphorus than annual lespedeza (Weathers, 1938). Little is known of the content of trace elements in sericea.

6. Establishment

The annual lespedezas are probably the easiest to establish of any of the major forage legumes. This is particularly true of Korean, which germinates quickly and grows rapidly in the early seedling stage. Under adverse conditions, as created by summer drought or infertile soil, the lespedezas often succeed when all other species fail. For this reason, lespedeza often is included in mixtures as a form of insurance.

It is a general practice to sow lespedeza in the winter on fall-sown grasses or small grains, on old established grass sods, or in thinning legumes. The seed is simply broadcast on the surface of the ground. Lespedeza thus seeded is subject to damage from late spring freezes in about the same degree as other legumes. To avoid this, seedings may be delayed until about two weeks before the average date of the last freeze, in which case it is advisable to drill the seed into fall-sown grains or established sods so that it becomes covered properly. In Georgia, Stephens (1952) recommended that light tillage be given to dense, sod-forming grasses in which the legume is to be sown. The

seeding rate varies from 15 to 40 pounds per acre, depending on the variety, the mixture, and other factors.

The difficulty of establishing sericea has been one of the factors limiting its use. The seedlings grow slowly, are not aggressive, and suffer greatly from competition with other species. Although a surprisingly good stand of seedlings may survive the competition, the plants are small and susceptible to winter injury, and may require another full growing season to reach maturity.

The most dependable practice is to sow the sericea by itself in early spring on a prepared seed bed at the per acre rate of 30 or 40 pounds of hulled, scarified seed (Bailey, 1951). Late-winter seedings made on the surface of the soil, or early-spring seedings drilled into the soil sometimes are successful on small grains, but as a whole this practice is not dependable.

7. Hay and Seed Production

The annual lespedezas and sericea produce abundant hay under favorable conditions, which is easily cured or ensiled because of low moisture content. Annual lespedezas usually yield about 1 ton of hay per acre, but they have been reported to yield over 4 tons under ideal conditions (Essary, 1921). In Missouri, unpublished data show that Korean lespedeza, following small grains moderately fertilized and harvested for grain, usually has produced about 1 ton of hay. Following winter barley, the least competitive of the small grains, hay yields have averaged 1.5 tons. The highest hay yield obtained after barley was 2.5 tons. Following timothy or orchardgrass harvested early in the spring for hay or pasture, the aftermath, composed mostly of Korean, has amounted to nearly 1 ton of hay.

Annual lespedeza hay should be cut in early bloom or earlier. Early cutting has several advantages. The legume is more nutritious, weeds are less advanced, the stand is less likely to be killed, and a much larger aftermath is obtained for reseeding or for pasture. Under very favorable conditions, the aftermath may make a second hay crop or be harvested for seed.

Annual lespedezas produce about 200 or 300 pounds of seed per acre under average farm conditions, with yields of 600 pounds not uncommon. In general, conditions that favor high hay yields favor high seed yields. Drought during the blooming and ripening stages greatly reduces the seed yield. The seed crop is harvested directly with the combine as soon as the leaves become dry from maturity or killing frost.

Sericea should be cut when 10 or 12 inches tall for the highest quality of hay. With this mangement it should make two to four cut-

tings yielding about 1 ton at each cutting. On less productive soils, not over two cuttings should be made, but on the more productive soils three or more cuttings may be made without serious injury to the stand. The last cutting should be made at least two months before the expected killing frost date to allow adequate root storage before winter. Taking a seed crop after growth has stopped does not harm the stand.

Sericea produces yields of seed ranging from 300 to 900 pounds per acre. The largest yields are made if the total season's growth is allowed to accumulate and mature. However, growers often prefer to harvest one cutting of hay because they obtain satisfactory yields of seed from the second crop, and the less coarse, woody growth makes for easier combining. Yields are greatly reduced by drought during the blooming and seed-forming stages. Most of the seed crop is harvested directly with the combine, and because the mature seed shatters badly, it is becoming common to harvest before the leaves become dry from maturity or frost (Bailey, 1951).

8. Soil Conservation and Improvement

Annual lespedezas are effective in controlling erosion and improving the soil. They are most effective if grown under levels of soil fertility adequate for vigorous growth, and if managed so that a considerable portion of the crop remains on the land. They greatly increase the organic matter content and the aggregation of the soil. In mixtures with grasses, the lespedezas contribute their own growth to the cover and furnish nitrogen for increased vigor of the grasses.

Karraker *et al.* (1950) studied nitrogen fixation and nitrogen losses in soils on which Korean was grown alone or with bluegrass. Korean fixed 206 pounds of nitrogen per acre annually when grown alone. It fixed 149 pounds when grown with bluegrass, and was 39 per cent more efficient in fixing nitrogen per pound of legume dry matter than when grown by itself. About 58 pounds of nitrogen per acre was lost annually by leaching in Korean grown alone. Most of the loss took place during late fall, winter, and early spring. This loss may be largely prevented by using a rye cover crop seeded in the fall. Winter cover crops not only conserve nitrogen but also protect against erosion in lespedeza stubble that is too sparse to give adequate protection.

Snider (1946) found that the tops and roots of Korean contained 83 and 30 pounds of nitrogen per acre, respectively. Albrecht and Klemme (1939) found 81 pounds in the tops and roots combined.

It has been demonstrated amply that lespedeza will provide enough nitrogen to produce good yields of corn, cotton, or other crops (Pieters, 1939). However, unless the phosphorus and potassium levels have been

maintained in the soil, the crops which follow lespedeza will have great need for those elements (Rogers, 1945).

Sericea is now widely and successfully used for erosion control. The highly lignified residues rot slowly and give year-round protective cover. When a thick stand is established and is managed so that a leaf mulch accumulates, it gives almost complete protection.

Fletcher and Livingston (1949) measured soil improvement under sericea used for rehabilitation of eroded and abandoned land. The litter accumulation at the soil surface amounted to 7.28 tons dry weight per acre, and had a water-holding capacity of 0.15 inch. This legume in less than eight years of occupancy on the unfertilized, eroded site had greatly improved the physical properties in the upper several inches of soil in terms of changes in volume weight, total porosity, volume of noncapillary pores, rate of surface water intake and subsurface transmission, and increased air-flow rate. Unpublished results of this same study showed that in the upper 7 inches of soil, sericea had increased the per cent base saturation and had added over 350 pounds of nitrogen per acre, not including that in the mulch.

Even with removal of part of the growth, vigorous stands of sericea accumulate nitrogen. Mooers and Hazelwood (1945) found that in 15 years of occupancy, this legume added 750 pounds of nitrogen per acre to the soil. The yield of the first crop of corn following sericea was 70 and that of the second crop 66 bushels per acre. Following no legume, corn produced 18 bushels on the same soil. The authors concluded that land which has been in high-yielding sericea can be expected to give good yields of corn for several successive years.

In addition to being used for feed, soil protection, and soil improvement on erosive cropland, sericea is used for turn-row borders in cultivated fields, stabilizing terraces, cover in waterways where slopes are less than 5 per cent, control of shallow gullies with naturally sloping banks or of deeper gullies with graded banks, and cover on the more gently sloping roadbanks (Bailey, 1951). Annual lespedezas may also be used for most of these purposes.

9. Weed Control

Weeds, especially the summer annual weeds, are troublesome in volunteer lespedeza stands, where they impair the value of the crop for hay or pasture. Mowing gives satisfactory control of some of the weedy species but not others, and has the disadvantages of destroying much of the legume herbage that is needed for feed. Rotation grazing permits mowing without loss of herbage. Growing lespedeza in small grains or in grass provides only partial control of weeds.

Eventually herbicides may be found that will selectively eliminate

troublesome weeds in annual lespedezas. A survey of the literature indicates that most of the chemicals presently used for weed control eliminate the legume or prevent its reseeding.

The most promising herbicide for controlling weeds in lespedeza is 2,4-D. Amine salt formulations are less likely to injure the crop than ester formulations. A number of investigators have used this chemical for controlling various broad-leaved weeds in grass-lespedeza mixtures; this has resulted in large increases in forage production. Although young lespedeza is injured by low rates of 2, 4-D, by the time it is 6 inches high it will tolerate the chemical at the rate of 1 or 2 pounds per acre. This permits the control of many weedy broad-leaved species. When the lespedeza reaches the bloom stage it is injured to a much greater extent than at the earlier stage (Elder, 1951). In some cases lespedeza has been sprayed in May or June and again in August with little injury (Harris, 1952).

Dodder is a serious pest of annual sericea lespedeza. Close grazing and mowing the hay at early stages are practical methods of control. Small patches of dodder can be eliminated by killing the lespedeza with herbicides or by mowing in the early hay stage.

Weedy grasses in sericea can be controlled to a considerable degree by following good production practices which maintain dense, vigorous stands of the legume. Proper cutting management and proper fertilization are important.

Very little information is available on the use of herbicides on sericea. There are indications that 2,4-D amine may be used on sericea 6 inches high at rates of 1 or 2 pounds per acre without serious injury.

10. Insects and Diseases

The lespedezas are remarkably free from serious insect damage. However, several insects feed on the crop and a few occasionally cause economic losses. The annual lespedezas may be heavily defoliated by grasshoppers, but only after most other crop plants have been eaten. Army worms usually destroy the seedling plants of lespedeza if they destroy the small grain crop in which it is growing. The larvae of the cranefly, *Tipula simplex* Doane, have caused considerable damage in the spring to young stands of lespedeza in Kentucky, but may be controlled with parathion, aldrin, or dieldrin (Rodriguez, 1954). The alfalfa hopper, *Stictocephala festina*, is capable of severely damaging or killing lespedeza and of encouraging diseases (Atkins, 1950).

Sericea may suffer light defoliation by any one of several insects including grasshoppers, beetles, and caterpillars. Army worms occasionally destroy a cutting of hay or a seed crop. The lespedeza web-

worm, *Tetralopha scortealis*, infrequently causes heavy defoliation and reduced seed yields. Annual lespedeza also may be attacked by this pest, but the varieties differ in susceptibility (Stuckey, 1945). Sericea may be injured by the three-cornered leafhopper and other stem girdlers (Bailey, 1951), and by the larvae of the June bug (Pieters *et al.*, 1950).

Economic losses caused by diseases in the annual lespedezas appear to be much greater than those caused by insects. Bacterial wilt, *Xanthomonas lespedezae*, is serious in the northern part of the Lespedeza Belt, and Korean lespedeza is more susceptible to damage than most of the other commonly grown varieties of the annual lespedezas (Offutt and Baldridge, 1956). The entire plant may wilt and die, but usually only part of the leaves wilt, accompanied by stunting and considerable reduction in the forage yield.

Tar spot, *Phyllachora* sp., causes heavy spotting of the leaves, with subsequent defoliation and reduction in yield (Hanson *et al.*, 1956). It is known to occur on Korean lespedeza in Missouri and North Carolina. This disease was reported in Texas by Dana *et al.* (1930).

Rhizoctonia solani causes damping off in young plants; in older plants it causes blighting and wilting of the foliage. *Sclerotium rolfsii* causes basal stem rotting and rapid wilting of plants; the blighted plants may be covered near the ground level with a white cottony growth bearing small, brown fruiting bodies. Both of these diseases cause considerable damage to lespedeza in the Cotton Belt.

Other diseases which at times cause economic losses are anthracnose incited by *Glomerella cingulata*, and charcoal root rot incited by *Sclerotium bataticola*. Powdery mildew of the leaves, incited by *Microsphaera diffusa*, is of widespread occurrence, but there is little evidence that it causes serious damage to the crop. *Sphaeropsis* sp. and *Diaporthe* sp. may be found on lespedeza but are of little economic significance.

Several kinds of nematodes attack the annual lespedezas, including root-knot nematodes, *Meloidogyne* sp., meadow nematodes, *Pratylenchus* sp., sting nematodes, *Belonolaimus* sp., and cyst-forming nematodes, *Heterodera* sp. The root-knot nematodes are known to cause serious economic losses on sandy soils, making it advisable to plant the relatively resistant variety ROWAN (Hanson *et al.*, 1953). The soybean cyst nematode, *Heterodera glycines*, attacks annual lespedeza as willingly as soybeans and in the future may become a serious pest.

Sericea is relatively free from attacks by diseases. Apparently it is susceptible to many of the root-knot nematodes, and one report of stem blight, probably caused by *Phoma* sp., has been cited by Pieters *et al.* (1950). Sericea is susceptible to cotton root rot, a disease which is confined largely to the blacklands of Texas.

III. Lespedeza Breeding and Improvement

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1. Introduction

The rapid expansion in annual lespedeza acreage during the two decades following the introduction of Korean focused attention on certain production problems and resulted in increased interest in lespedeza breeding. The lespedezas have been generally considered to be quite free from diseases; however, in recent years bacterial wilt, root-knot, and certain foliar diseases have become of sufficient importance to demand attention. Development of disease-resistant varieties is now of first concern in lespedeza improvement. In addition, varieties with greater general productivity are desired.

Three species in the genus *Lespedeza* are of agricultural importance in the United States. Each was introduced from eastern Asia, which appears to be the center of origin of *Lespedeza.* Two of the three species comprise the annuals in the genus, *L. stipulacea* and *L. striata,* known as Korean and striate lespedeza, respectively. *L. cuneata,* commonly called sericea, is an herbaceous perennial, with new growth coming each spring from the crown. In the United States these three species play an important role as hay, pasture, and soil-conserving crops throughout their areas of adaptation. A few other species such as *L. bicolor* are of minor importance in soil and wild life conservation or as ornamentals.

Selection in the few plant introductions received from Asia has revealed an array of biotypes covering a wide range in growth habit, maturity, and resistance to disease. In the annuals procumbent types have proved valuable in pastures, whereas upright types have been more suited for hay production. A wide range in maturity provided types adapted from the Gulf Coast to central Indiana and Illinois. Thus there appears to be a sufficiently broad genetic base in the two annual species to permit improvement in existing varieties.

Interest in the improvement of sericea has also increased in the past ten years with the growing appreciation of its value as a forage and soil-conserving crop. Low palatability, however, appears to have delayed wide-scale adoption of this plant as a hay and pasture crop. Sericea is also slow to become established; growth is usually too short to harvest in the first year, and weed problems often result. Several states now have breeding work on this legume under way. Breeding objec-

tives have been directed toward improving quality of forage, yield, and seedling vigor. Studies on the genetics and breeding of sericea are as yet quite limited.

2. *Plant Introductions and Varieties*

a. The Annuals. The first lespedeza to be grown commercially in the United States is now known as common lespedeza, a variety of *L. striata.* This variety is small, fine-stemmed, and almost prostrate except in thick stands. It is best adapted to the area from northern Tennessee to the Gulf of Mexico; however, very little common lespedeza is now grown for hay, having been replaced by the taller growing varieties. Its use is largely restricted to pastures, where it reseeds.

TENNESSEE 76 resulted from a program of selection, initiated in 1912 by the Tennessee Agricultural Experiment Station, to improve common lespedeza (Essary, 1921). After several years of testing strains collected over the state, a number of upright plants appeared in a strain carried as No. 76. These plants were increased and released as TENNESSEE 76. It was quite popular until the advent of the taller growing varieties, Korean and Kobe. TENNESSEE 76 appears to have been lost as a variety.

Kobe lespedeza, *L. striata,* resulted from an introduction into the United States from Japan in 1919 (Pieters, 1934). Kobe is much larger and coarser than common lespedeza, with larger leaves and seed, somewhat later in maturity and with an upright type of growth. It is the principal variety of striate lespedeza currently in production. The main area of production of Kobe is from the eastern seaboard to western Tennessee and from Kentucky south into the Coastal Plain areas of the Gulf Coast states. It is the most important lespedeza in the Coastal Plain areas.

Seed of Korean lespedeza, *L. stipulacea,* was sent to this country in 1919 by Dr. Ralph Mills, a medical missionary to Korea (Pieters and Van Eseltine, 1924). Korean has a more leafy appearance than Kobe, the leaflets being wider and somewhat ovate with a broad stipule. It is similar in size to Kobe but has a more spreading growth habit and matures seed almost a month earlier. The area in which it is principally grown extends from Maryland, Virginia, and North Carolina on the east to eastern Kansas and Oklahoma on the west. It also extends into Ohio, Illinois, and Indiana and into the piedmont areas of South Carolina, Georgia, and Alabama.

During the period of rapid increase in lespedeza acreage, earlier maturing varieties of Korean were of considerable interest in the hope of extending the northern limits of lespedeza production. Several early varieties have been released; however, none have been widely used. HARBIN lespedeza resulted from a seed lot obtained in 1926 from a

Russian cemetery at Harbin in the province of Kirin, Manchuria (Pieters, 1934). This was an exceptionally early variety but yield of forage was too low for it to be of much value. Early Korean, F.C. 19,604, was a more productive variety, later in maturity than HARBIN but earlier than Korean (Pieters, 1939). Shortly after its release in 1936 this variety was found to be particularly susceptible to a new disease of lespedeza, bacterial wilt, which prevented its wide-scale use.

A program of selection to develop early-maturing, wilt-resistant varieties was undertaken by Wilsie and Hughes (1947). A source of resistance was found in plants that apparently survived bacterial wilt infection along road banks near Cedar Rapids, Iowa. Seed were collected in 1938 and the following year inoculation tests indicated a satisfactory degree of resistance in certain lines. Continued testing and selection resulted in the release of three wilt-resistant lines of suitable maturity. IOWA 6 was the earliest; IOWA 39 was slightly later and tolerant to high-lime soils; and IOWA 48 was still later and the most productive. Of these varieties current production is limited to a relatively small acreage of IOWA 6 (C. P. Wilsie, correspondence).

A seed lot of a type approximately three weeks later in maturity than commercial Korean was introduced in 1936 by the Division of Plant Introduction and Exploration under the number P.I. 116,138. The variety CLIMAX, released in 1944, was essentially the same as P.I. 116,138. Selection within this introduction revealed several distinct morphological types. CLIMAX as now constituted consists of the increase of one of the lines derived from the original introduction. It is taller and more upright than commercial Korean and is a good seed producer. Being later in maturity, CLIMAX extends Korean production somewhat southward.

ROWAN lespedeza, possessing moderate resistance to two forms of root-knot nematodes, *Meloidogyne incognita* and *M. incognita* var. *acrita*, and to powdery mildew, was released by the North Carolina Agricultural Experiment Station in cooperation with the U.S. Department of Agriculture in 1952 (Hanson *et al.*, 1953). ROWAN is a plant selection tracing to a seed lot obtained originally from Rowan County, North Carolina, and in leaf and stem characteristics is quite similar to commercial Korean. Tests on root-knot nematode infested fields and under controlled inoculations demonstrated the superior performance of this variety and its low susceptibility to the two nematode forms named. Seed of ROWAN is being increased under the state seed certification programs.

b. Sericea. The history and development of the perennial lespedezas in the United States has been described by Pieters *et al.* (1950). Sericea lespedeza, *L. cuneata,* appeared most promising of the herbaceous

perennials for forage and soil improvement. Introductions and selections from a number of introductions were tested at the Arlington Experimental Farm, Arlington, Virginia, and at various experiment stations in the Southeast. Of these early strains one variety, ARLINGTON, F.C. 19,284, resulting from the increase of a vigorous plant in a volunteer stand at Arlington Experiment Farm was released. It was vigorous, uniform, and made good seed yields in early tests. Presently there is a small acreage of ARLINGTON in the seed certification programs in South Carolina, Georgia, and Mississippi.

3. *Mode of Reproduction and Crossing Technique*

Early efforts to obtain crosses in lespedeza were without success. Essary (1921) reported failure to obtain crosses within *L. striata;* flowers were delicate and almost always fell off on being cross-pollinated. Others experienced similar results. McKee and Hyland (1941) indicated that efforts to make crosses in lespedeza were unsuccessful and noted that crosses had not been reported earlier. Failure to obtain crosses created an interest in the mode of reproduction in lespedeza and the cause of crossing failures.

a. Korean. (1) Floral morphology and reproduction. According to McKee and Hyland (1941) most of the herbaceous species of lespedeza produce seed from both petaliferous and apetalous flowers. The latter are known to be the more fertile, but until recently little was known concerning flower development and the method of reproduction in each flower type.

Studies on the morphology and development of flowers in *L. stipulacea,* basic to the development of a crossing technique, were begun by Hanson (1943) prior to World War II and continued later (Hanson, 1953a). Detailed examination revealed that apetalous flowers are complete, the corolla being quite small and remaining enclosed in the calyx until forced out by the growing seed pod. In view of the presence of small petals in the "apetalous" flowers, the terms "chasmogamous" and "cleistogamous" came into usage in preference to "petaliferous" and "apetalous" found previously in the literature. Hanson's studies also revealed that reproduction is sexual in the cleistogamous flowers as well as the showy (chasmogamous) flowers. The style was hooked, with the stigma touching one or more anthers. The anthers did not dehisce in cleistogamous flowers, the pollen grains germinating inside the anther and the pollen tube growing through the anther wall and into the stigma. Fusion stages were not observed in a cytological study of the cleistogamous flowers, but genetic evidence for fertilization was found in the segregation occurring in populations grown from

cleistogamous seed of F_1 hybrids. The author concluded that the essential features of meiosis and microgametogenesis appeared to be identical in the two flower types.

Proportion of cleistogamous to chasmogamous flowers was found to be determined largely by environmental conditions (Hanson, 1943). Temperature appeared to be a major factor; flowers were predominantly chasmogamous at 80° F. and cleistogamous at 70° F. Light intensity and day length also appeared to be related to the proportion of the two flower types.

(*2*) *Controlled hybridization in Korean.* A report by Hanson (1953b) described a crossing technique found to be quite successful for *L. stipulacea.* The technique involved pollinating in the bud stage and omitting emasculation. Crossing was limited to chasmogamous flowers because of the structure and small size of the cleistogamous flowers. Flower buds were pollinated 1 to 2 days prior to anthesis. The buds were rather delicate and tended to fall easily, so manipulation had to be held to a minimum. Gentle pressure applied with the thumb and forefinger to the ventral and dorsal sides usually opened the tip of the bud and exposed the stigma. When the pressure did not open the bud sufficiently a sharp probe was used to separate the keel petals. Cross-pollination was accomplished by dusting the stigma with the distal end of the sexual column of the mature flower of the male parent. All cross-pollinations were made in the field, where showy flowers appeared more fertile than in the greenhouse. Although an occasional self-pollination occurred, omitting emasculation did not appear to be of serious consequence.

b. Sericea and Other Perennials. (*1*) *Mode of reproduction.* Sericea is facultatively cleistogamous, in this resembling the annual lespedezas. Available evidence now indicates that the mode of pollination in cleistogamous flowers is identical to the unique mechanism described for Korean lespedeza by Hanson (1943, 1953a). In a study on reproduction in perennial species Hanson and Cope (1955a) found that cleistogamous flowers of sericea were only about 1 to 1.5 mm. in length at maturity and about one-tenth to one-sixth as long as the chasmogamous flowers. They were complete, with petals somewhat shorter than the calyx. The flower remained closed until the young ovary forced the calyx lobes apart, thus permitting little or no opportunity for natural crossing in the cleistogamous flowers. From a study of segregation in F_2 progenies of interspecific hybrids these authors showed quite conclusively that the cleistogamous flowers were sexual and self-fertilized. This was consistent with earlier observations by Stitt (1946). Unfortunately the earlier literature was confusing on this point. A unisexually pistillate condition for cleistogamous flowers, for

example, is indicated by Gray's *Manual of Botany* (Fernald, 1950), but this appears to be in error.

McKee and Hyland (1941) pointed out that immature and mature pods from the two flower types could be differentiated in sericea by the old stylar tissue forming the tip of the pods. The tips of the pods from cleistogamous flowers were hooked in contrast to the straight, bent, or slightly curled tops of the chasmogamous flowers.

(*2*) *Natural crossing in sericea.* The chasmogamous flowers, in contrast to the cleistogamous flowers, appear to be mostly cross-pollinated. Stitt (1946) reported 61 to 81 per cent crossing of sericea lines, and Hanson and Cope (1955a) reported 75 per cent.

As pointed out by Hanson and Cope (1955a) the occurrence of predominantly outcrossed (chasmogamous) and naturally self-pollinated (cleistogamous) flowers on the same plant is an aid to genetic and breeding studies. Because the mature fruits from the two types of flowers can readily be separated on the basis of morphological differences, a convenient method of determining the effects of inbreeding and outcrossing is available.

4. Breeding and Inheritance Studies

a. Korean. (*1*) *Flower color and other characters.* Successful crosses in lespedeza led to a series of inheritance studies. In the first of these studies (Hanson, 1953c) results of segregation for each of five characters were reported for F_2 populations from three crosses. Flower color appeared to be controlled by not more than two major gene pairs, genes for moderate purplish-red being partially dominant to pale purplish-red. More than two gene pairs were involved in the inheritance of powdery mildew resistance, date of first bloom, growth habit (procumbent vs. upright), and erectness of main stem. Chi-square tests for independence of characters indicated probable linkage of certain genes for flower color and date of first bloom, flower color and powdery mildew resistance, and date of first bloom and erectness of main stem. In no case did the linkages appear to be sufficiently close to seriously hinder selection for any particular combination of characters.

(*2*) *Inheritance of yield.* Sandal (1954) studied F_4 plant-to-plant variation in 36 families representing two populations from Hanson's (1953a) crosses, his study being made at Fayetteville, Arkansas. Highly significant differences were found among families in spread (forage index), seed yield, and date of flowering. Within-family differences were greatest for date of flowering, with seed yield being intermediate and forage index lowest. Pooled correlation coefficients (single plant basis) of $+0.485^{**}$ between seed yield and spread and

—0.202** between seed yield and date of flowering were obtained. Corresponding correlation coefficients computed from family means were +0.620** and —0.562**. The correlation coefficient between date of flowering and spread was +0.226** on a single plant basis, but a nonsignificant —0.020 when family means were used. The correlation between seed yield and spread was the only one having any useful prediction value. Hanson *et al.* (1956) also obtained a positive correlation between forage yield (total yield at maturity) and seed yield of segregating Korean lines. Vigor scores on July 1 and August 15 together with actual yields indicated that earlier flowering families tended to have greater early vigor than late-maturing families but less total growth at the end of the season. The negative correlation between seed yield and date of flowering, found by Sandal, was not evident in this study. The lack of agreement between the two studies on this point was possibly related to differences in growing seasons, the longer growth period in Hanson's study allowing greater seed production in late varieties.

The study by Hanson *et al.* (1956), which was conducted at two locations for two years, also provided estimates of genetic, environmental, and interaction variances. Among the more significant results were the relatively large variances due to genotype × year interactions, being approximately equal in magnitude to the genetic variances. The difference in yearly weather patterns was considered to be an important factor, indicating the need for testing varieties over a period of years. Heritability estimates indicated opportunity for improvement of both forage yield and seed yield in each population, with expected genetic advance being higher for seed yield than for forage yield. Selection on the basis of vigor scores taken the middle of August was expected to be only slightly less effective than selection for forage yield in two populations. In the third population, segregating for procumbent vs. upright growth habit, however, heritability of vigor was very low, apparently resulting from difficulty in scoring vigor accurately in such a population. Scores made on August 15 were more reliable than scores on July 1.

(3) *Resistance to tar spot.* Tar spot caused by *Phyllachora* sp., reported on *L. stipulacea* for the first time by Hanson *et al.* (1956), was found to be of sufficient economic importance to receive consideration in breeding programs. The tar spot reaction of 30 F_7 lines, progeny of a cross between ROWAN and a late-maturing strain, was considered in relation to leaf loss, dates of flowering and maturity, and hay and seed yields. The greatest effect of tar spot was reduction of seed yield. The correlation of tar spot score with seed yield was —0.84**, the most susceptible lines yielding only 30 per cent as much seed as the most

resistant lines. Although there was no indication of lowered hay yields, there was probably a reduction in quality due to leaf loss. Defoliation and premature ripening of susceptible lines was shown by correlations of +0.88** and −0.42*, respectively, for leaf loss and maturity with tar spot score. No infection was observed on Kobe. ROWAN was moderately resistant.

(*4*) *Resistance to root-knot nematodes.* Root-knot nematode infection was associated with severe stunting and loss of stands of annual lespedeza in the Coastal Plain area of Georgia (Stephens, 1942). Lespedeza following cultivated crops on upland soils was particularly damaged, whereas that on moist bottom land showed little effect on root-knot. The conclusion was made that the annual lespedezas are unable to tolerate root-knot nematodes when associated with drought. Subsequent experience has supported Stephens' report and has shown that both the annual species are highly susceptible to certain forms of root-knot nematodes. Smith and Taylor (1947) reported Korean to be more susceptible than Kobe.

Differences between strains within species of lespedeza in resistance to root-knot nematodes were first reported by Hanson *et al.* (1953). Eight strains each of Korean and Kobe lespedeza were grown on root-knot nematode infested soil at the Willard Sub-station in the Coastal Plain area of North Carolina and also at four other locations over the state. One of the Korean strains, F.C. 31,480–43, was also tested with commercial Korean and Kobe in greenhouse benches filled with root-knot nematode infested soil. Significant differences in yield occurred among strains of both Korean and Kobe. The differences were directly related to root-knot nematode resistance as measured by extent of gall formation. Differences in forage yield between strains decreased with lower levels of root-knot injury. Korean was more susceptible than Kobe, as indicated both by lower forage yield and higher nematode indices of Korean. F.C. 31,480–43 made the highest yields of any of the Korean strains and had the lowest root-knot index. It was particularly outstanding on the root-knot nematode infested soils at Willard and in the greenhouse. F.C. 31,480–43 was released for production under the name ROWAN.

The annual lespedezas appear to be generally quite susceptible to all of the more prevalent species of root-knot nematodes. Wells *et al.* (1953) tested the susceptibility of ROWAN, commercial Korean, and Kobe to five species and forms. Plants were grown in pots in the greenhouse using steamed soil inoculated with cultures of the respective nematode species, *Meloidogyne incognita*, *Meloidogyne incognita* var. *acrita*, *M. hapla*, *M. arenaria*, and *M. javanica.* ROWAN was moderately resistant to *M. incognita* and *M. incognita* var. *acrita*, suggesting that

one or both of these forms prevailed at the locations where ROWAN showed resistance. Korean and Kobe were highly susceptible to each of the species of *Meloidogyne*.

Hanson *et al.* (1954) studied the inheritance of the root-knot reaction in the F_5 generation from the cross between ROWAN, having moderate resistance to two forms of root-knot nematodes, and F.C. 31,850, a late-maturing strain. Tests were made in the greenhouse under controlled conditions. The authors reported heritability estimates of 87.1 and 71.7 per cent of family means, respectively, for reaction to *M. incognita* and *M. incognita* var. *acrita*. The expected genetic advance from selecting the top 5 per cent of the families was 40.4 and 28.9 per cent of the respective population mean scores. These estimates indicated that rapid progress could be made in nematode resistance by selecting among the families. Selection within families appeared to provide opportunity for additional improvement. A high genetic correlation of +0.93 for reaction to *M. incognita* and *M. incognita* var. *acrita* indicated that certain genes for resistance to one of the nematode forms also conferred resistance to the other. The study also indicated better control of environmental variation than was possible under field conditions.

b. Sericea. (1) Improving palatability. Efforts to improve sericea have been concerned primarily with palatability, but progress in this direction has been somewhat slow. In the first place, the causes of low palatability have not been fully determined. The tannin content of the leaves and morphological characteristics of the stems are known to be associated with palatability; however, the relative effect of each character is somewhat uncertain, and it is possible that other characters may also affect palatability. In addition, tannin analyses are expensive and time-consuming, and methods for measuring morphological characters need to be refined.

All species of lespedeza analyzed have been found to contain leaf tannin. In the annual species the tannin content apparently is too low to noticeably affect palatability. In sericea it is known that the tannin content is an important factor in palatability, and possibly it plays a major role. Feeding trials have demonstrated the preference of livestock for low-tannin lines (Wilkins *et al.*, 1953), but whether there are marked differences in types of tannin and relative astringency is unknown.

That tannin content is a heritable character was first shown by Stitt (1943). Analyses of vegetatively propagated clones revealed differences in the tannin content, and further analyses of individual plants in different lines indicated the possibility of obtaining low-tannin lines by selection. Within-line variation was greater in certain lines than

others. It was found that the tannin content was negatively correlated with leafiness but positively correlating with plant height, number of shoots, and yield; this would indicate difficulty in incorporating the factor for low tannin content into a vigorous high-yielding variety.

Bates and Henson (1955), studying F_2 segregation in populations from three controlled crosses, also found the tannin content to be a heritable character. Heritability was estimated to be about 40 per cent of the F_2 variation. The tannin content was not correlated with plant height. Neither was there a significant correlation of the tannin content with maturity, flower color, plant color, seed size, nor per cent cleistogamous seed. The lack of agreement between this report and that of Stitt on the association of vigor and tannin content may be due both to different populations studied and to environmental effect on the tannin content.

The natural variation within sericea populations apparently includes a wide range in the tannin content. Populations of 1612 and 1206 plants were studied by J. M. Elrod (unpublished) and Donnelly (1954), respectively. The tannin content ranged approximately from 2 to 11 per cent in both populations. The effects of nongenetic factors in such populations are not well understood. Factors other than genetic are known to affect the tannin content of sericea. Among these are stage of growth, season, light intensity, and soil fertility. These factors have been discussed in the section on management.

Donnelly (1954) found that the size and pliability of stems, as well as the tannin content, were important in palatability. Steers allowed to graze spaced plants preferred those with small pliable stems and low tannin content. Selection for small pliable stems appeared quite feasible since approximately one-third of the plants in the test were of this type.

Other characters, which are directly related to quality, if not to palatability, have been shown by Donnelly and Hawkins (1954) to vary between lines of sericea. Among these were protein content and quality, lignin content, and leafiness. Protein in sericea was only 50 per cent as digestible as alfalfa protein, according to these authors; however, certain inbred lines were found with relatively high protein digestibility. A variation in leafiness of 15 per cent was observed in the inbred lines studied. Lines having fine pliable stems, relatively high digestible protein content, or good leafiness were isolated; and confidence was expressed in combining these characteristics in a more nutritious variety.

(*2*) *Inheritance of other characters.* Differences between sericea lines in growth type and other morphological characters have been noted, beginning with the introductions first tested at the Arlington Experiment Farm. However, studies on inheritance and the possible use

of these characters in sericea breeding are meager. Stitt (1943) found wide differences between sericea lines in plant height, number of shoots, leafiness, per cent dry matter, and yield. A procumbent line, studied by Stitt (1946), appeared to be homozygous for this character, since all selfed progeny were procumbent. Certain plants from showy flowers were assurgent and considered to be the result of natural crossing. The F_2 distributions indicated a somewhat complex type of inheritance.

Bates and Henson (1955) studied the inheritance of eight characters in populations from three controlled crosses in sericea. In addition to tannin (discussed earlier) the per cent of the variability in F_2 populations found to be heritable was as follows: plant height—55 to 60, maturity—90, flower color—92, plant color—90, seed size—75 to 91, and proportion of seed from cleistogamous flowers—36. However, these values were obtained using genetic variances estimated for one location and one year, which contain any variance arising from the effect of genotype environment interactions. Thus they may result in overestimates of heritability, depending on the relative magnitude of the interactions. In Korean lespedeza (Hanson *et al.*, 1956) the genotype $\times$ year interactions were found to be so large that a single test would have given entirely misleading estimates of heritability. The number of genes involved in the inheritance of the characters in the study by Bates and Henson (1955) was estimated as four for seed size and several times this number for each of the other characters.

Although the inheritance of most of the characters studied in sericea has been found to be quite complex, a relatively simply inherited character has also been reported. The expression of a dwarf condition in sericea was interpreted by Hanson and Cope (1956) as resulting from a recessive mutant gene in the homozygous condition. The dwarf was characterized by shortened internodes, small leaves, and moderately light green color of foliage.

From field observations it has generally been concluded that sericea is quite resistant to root-knot nematodes. Controlled inoculations by Wells *et al.* (1954) demonstrated a wide variation among sericea strains in root-knot resistance. Sericea lines reacted differently to the five root-knot forms tested, *Meloidogyne incognita, M. incognita* var. *acrita, M. hapla, M. arenaria,* and *M. javanica.* Lines were isolated which were moderately resistant to one or more of the root-knot forms. Certain lines were quite susceptible to all forms of root-knot.

(3) *Evidence for heterosis.* Donnelly (1955) found that the chasmogamous progenies of ten randomly chosen plants yielded on the average of 25 per cent more forage and 40 per cent more seed than the cleistogamous progenies. Results were interpreted as indicating a significant degree of heterosis in sericea, with marked differences among

the ten plants in general combining ability. On this basis it was suggested that a breeding program in sericea utilizing hybrid vigor should produce varieties with increased forage and seed production. Hanson *et al.* (1956) also reported evidence of heterosis in sericea. Spaced progenies from chasmogamous flowers of 33 lines yielded 11 per cent more forage than progenies from the cleistogamous flowers of the corresponding lines.

The production of a high proportion of chasmogamous flowers thus becomes important to insure a maximum of crossing. McKee and Hyland (1941) reported differences among lines and seasons in proportion of seed produced from the two flower types. Brinkley *et al.* (1956) and P. R. Henson (unpublished) also noted differences between lines, the crop saved for seed, and locations. Seed produced late in the season generally contains a higher proportion of seed from cleistogamous flowers than those produced earlier. The plant genotype, environmental conditions associated with specific location and crop harvested for seed, and the activity of the agents effecting cross-pollination each appears to affect the proportion of naturally outcrossed seed in sericea. Thus the use of heterosis in sericea is complicated by other problems in addition to isolating lines with good combining ability.

c. Interspecific Hybridization. Hanson and Cope (1955b) undertook a study to determine the degree of interfertility existing between species. This relationship was examined in 52 of the possible combinations among 13 species, 37 of the combinations including reciprocals involving *L. cuneata*, *L. stipulacea*, or *L. striata*. Interest in the study rested principally on the possible utilization of interspecific hybridization in lespedeza improvement. Five partially fertile but vigorous F_1 hybrids were obtained as follows: *L. cuneata* × *L. latissima*, *L. latissima* × *L. cuneata*, *L. cuneata* × *L. inschanica*, *L. hedysaroides* × *L. cuneata*, and *L. hedysaroides* × *L. inschanica*. Viable hybrids were not obtained from crosses between annual and perennial species or between perennial species introduced from Asia and those indigenous to North America. Available evidence indicated that fertilization occurred from cross-pollinations of *L. stipulacea* and *L. cuneata*, but whether embryo development was sufficient for successful culturing on artificial media was not determined. The successful crosses were between perennial species introduced from Asia. The crosses were fruitful in yielding a wide array of morphological forms of the perennial type.

Although *L. cuneata* previously had been reported as having $2n = 18$ (Cooper, 1936) and $n = 9$ chromosomes (Pierce, 1939), the number in the material studied by Hanson and Cope (1955b) was $n = 10$. These authors also reported $n = 10$ for *L. hedysaroides* and confirmed Pierce's (1939) report of $n = 10$ for *L. latissima*. *L. inschanica*

was found by Pierce (1939) to have $2n = 20$ chromosomes. These studies by Hanson and Cope (1955b) indicated a close phylogenetic relationship between *L. cuneata* and *L. latissima*, and between *L. inschanica* and *L. hedysaroides*. Since hybrids were obtained between the last two species and *L. cuneata*, the four species were set apart from the others investigated as an interrelated group. A diploid complement of 20 appears to be common to the four species. They had previously been placed in the "sericea group" by P. L. Ricker (Hanson and Cope, 1955b.)

d. Induced Polyploidy. Autotetraploid lines of *L. cuneata*, *L. stipulacea*, and *L. striata* have been developed from the treatment of the respective diploid species with colchicine (*a*) to determine whether interspecific hybrids might be obtained from any of the various combinations of diploid and tetraploid matings, and (*b*) to determine the agronomic characteristics of the tetraploid forms (Brinkley *et al.*, 1956). Regarding the first objective, viable hybrids were not obtained from any of the ten combinations of diploid and tetraploid crosses attempted among these three species. Embryo abortion, however, occurred at a later date in certain tetraploid × diploid matings than in matings attempted at the diploid level.

Chemical analyses were made for certain constituents in leaves of (*a*) diploid and tetraploid individuals of the C_0 and C_1 generations, and of diploid and tetraploid sectors of individual plants of the C_0 generation in *L. cuneata*, and (*b*) diploid and tetraploid C_2 lines of *L. stipulacea* and *L. striata*. In each case, the tannin content of the tetraploid was higher than that of the corresponding diploid form. The tetraploids also tended to be lower in total nitrogen, calcium, and phosphorus. The tetraploids had larger leaves and coarser stems, matured later, and yielded less hay and seed. Induced tetraploidy resulted in seed yields being reduced less in the two annual species than in *L. cuneata*.

Induced tetraploidy appeared to be a valuable tool in lespedeza breeding, but the autotetraploids themselves have not as yet shown any particular promise as forage plants.

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MEASUREMENT OF SOIL BULK DENSITY AND PENETRABILITY: A REVIEW OF METHODS*

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I. Introduction

Several properties of a soil mass change as the soil is compressed. Its bulk density increases, pore volume decreases, pore size distribution shifts toward a larger proportion of small pores, and pore space continuity is often decreased. These changes in void-solid relationships in turn affect the consistency of the soil and its capacity to conduct and retain air (Russell, 1952), water (Richards and Wadleigh, 1952), and heat (Richards, S. J., *et al.*, 1952).

There are, then, several properties which can serve as indicators of soil compactness. Numerous methods have been developed and are being used to characterize the physical condition of soil, of which compactness is a very important part. Reviews of methods for studying soil structure and aeration have been published by E. W. Russell (1938) and M. B. Russell (1949a). Since these surveys, a number of methods stressing the movement of fluids through the soil have been proposed. Kirkham (1946), Blake and Page (1948), Taylor (1949), Raney (1949), and Lemon and Erickson (1952) have proposed methods for measurement of gas flow and diffusion in soils. These methods are sensitive in detecting the effects of compaction but perhaps need some perfecting. Low (1954) has published recently a review of methods for measuring soil structure, several of which are useful in compaction studies.

* This paper is based on work done by the author at Rutgers University, the State University of New Jersey.

Each possible method of measurement is most suitable for the study of the physical condition of soil from a particular point of view. As pointed out by Russell (1949a), a complete description of soil structural condition is essentially impossible, and no single method should be considered best for measurement of structure. The same may be said about soil compactness. In the study of compaction, certain methods have important advantages. Compactness is normally thought of in terms of density or hardness, and it is most directly determined by measurement of the weight of material per unit volume or of the resistance of the mass to penetration.

Experiments designed to test the effect of tools and operations on the soil are virtually always field experiments, and as such have satisfactory precision only if sampling is thorough. A large number of measurements should be made, and consequently, the method used must be relatively rapid. The apparatus must be sturdy, rugged, simple, and portable. Finally, the method should be such that measurement of the property involved may be made to the maximum depth of the treatment effect with a minimum of plot disturbance. Here, then, are the characteristics by which the suitability of a method may be judged. Bulk density and penetrometer methods fit these conditions adequately, in addition to being quite fundamental indices of physical condition. Other methods of describing compactness may be more meaningful from the point of view of plant growth, but penetrability and density seem at present to be more suitable characteristics for field use. The principal shortcoming of these measurements lies in the difficulty of interpretation of data in terms of crop response.

Nevertheless, the two methods have been widely used in compaction studies with considerable success. In an ideal soil all the various properties affected by compaction would be strictly related. In field soils relationships exist, but often they are poorly defined. This paper will discuss the measurement of bulk density and penetrability, and the interpretation of data obtained. It is not intended to discount the value of other methods, but the discussion is thus limited because at the present time these two methods seem to be the most usable in field studies of soil compaction.

II. Soil Penetrometers

The penetrability of a soil to any probing is a rheological property depending on the texture, structure, mineralogical composition, moisture content, and compactness of the soil. As such, penetrability can serve only as a relative measure of compactness under conditions where the other controlling variables are held constant or can be accounted for from previously determined relationships. Penetrometer measure-

ments with the types of apparatus now in use can be made so rapidly in experimental sites under controlled conditions that the method has found widespread use in compaction studies. Published reports covering the design and use of several types of penetrometers have been reviewed by Bodman (1949). The various systems may be classified into two groups: the impact type (Keen and Cashen, 1932; McKibben and Hull, 1940; Parker and Jenny, 1945; Stone and Williams, 1939) and the continuous-stress indicating or recording types (Allyn and Work, 1941; Culpin, 1936; Davies, 1930; Henin, 1936; Proctor, 1933; Reed, 1940; Richards, S. J., 1941; Robertson and Hansen, 1950; Shaw, B. T., *et al.*, 1942). Penetrometers have been used to measure compaction (Culpin, 1936), (Keen and Cashen, 1932), to locate compact layers (Parker and Jenny, 1945; Reed, 1940), to estimate drawbar pull in plowing (Stone and Williams, 1939), and to measure soil moisture condition (Allyn and Work, 1941).

Shaw *et al.* (1942) used a recording continuous-stress type penetrometer in studies of soil compaction for a number of years, and concluded that this instrument was useful in field investigations. They decided that soil moisture was the dominant factor influencing the force required to penetrate a given soil type, but even so they were able to locate zones of maximum compaction.

Reed (1940) obtained penetrometer data under conditions of constant moisture and was able to describe the relative compaction of soil by rubber tires, steel lugs, and crawler tracks in terms of lateral spread and penetrability. Keen and Cashen (1932) used an impact penetrometer to measure compaction by sheep on a light sandy soil in England. They reported that the packing was evident to a depth of 10 cm., which indicated that they were able to locate the zone of consolidation. Culpin (1936) described several penetrometers and the advantages and disadvantages of each. The relationship of penetration by slow moving probes, revolver bullets, and plow shares with other soil properties was discussed. A general negative correlation between penetrometer data and emergence of spring oats was reported.

Klute and Jacobs (1949), using an impact-type penetrometer, found that compaction by sprayer and tractor wheels affected the penetrability of a Sassafras silt loam in the 0- to 5-inch layer but did not affect it in the 6- to 9-inch layer. No difference in penetrability relatable to differences in level of manure application was found, even though these did result in changes in the air space and bulk density. Browning *et al.* (1942) used a Rototiller soil-hardness gauge (Stone and Williams, 1939) to measure the effect of a cover crop on soil compactness. They reported that the condition measured by the penetrometer under a cover crop was probably influenced by crusting. It can be seen that

extreme care is necessary in the interpretation of data obtained from penetrometers in compaction studies.

In a study of the effect of cover crops on pore size distribution and penetrability using a Rototiller soil-hardness gauge (Stone and Williams, 1939), Lutz *et al.* (1946) found highly significant correlation between penetrability and 10 cm. porosity, and 60 cm. porosity. The correlation between penetrability and total porosity was significant. The soil studied in their experiments was predominantly a fine sandy loam.

Since something must be driven into the soil to make penetrometer measurements, Parker and Jenny (1945) used a King tube in order that cores could be removed at the same time for the estimation of bulk density. A Ramona loam soil was treated with several compactive efforts at two moisture levels. Resistance to penetration was measured by the amount of energy expended in driving the King tube 1 inch into the soil. Core weights (bulk densities) were determined on the cores removed by the tube. Both the resistance to penetration and the core weights increased with compactive effort. Parker and Jenny did not comment on the relationship between core weight and resistance value, but from their data it did not appear to be linear. They concluded that both resistance to penetration and bulk density corroborated the differences in water penetration obtained under the various treatments.

Jamison and Weaver (1952) recently suggested a method for adjusting penetrometer data into terms of soil porosity conditions and in particular with macroporosity, defined as the pores drained at 60 cm. tension. The best simple function giving high correlation with macroporosity in the Decatur clay and the sandy clay subsoil of the Greenville fine sandy loam was log $(\theta H^{1/2})$, where θ was the field moisture content and H the number of standard hammer blows required to cut a soil core. They reported that the hardness function can be used to estimate macroporosity and compares favorably with the latter in relationship to depth of rooting, growth, and height of cotton plants.

Although this paper is not a complete review of work with penetrometers, it can be concluded that under circumstances where comparisons can be made between different levels of tilth on soils having very similar particle size distributions, profile developments, and moisture contents, discrimination between levels of tilth can be accomplished with penetrometers. If, for example, significant differences in penetrometer data occur between treatments in field experiments on soil management, these differences imply, and can be used to represent, differences in aeration, permeability to water in most cases, and mechanical impedance to the growth of plant roots. However, it is important that the limitations of this method be kept constantly in mind.

A summarization of penetrometer methods may be aptly quoted from Bodman (1949): " . . . results of penetrometer measurements, though useful in examining the soil profile, assessing soil-crop relationships, and the effects of tillage treatments, and in many other ways, are not fundamental measurements independent of the apparatus used. Many soil variants, from one part of a field to another within a single soil type, may very greatly affect the penetrometer, so that the results of the empirical measurements are commonly difficult to interpret."

III. Measurement of Soil Bulk Density

Soil compactness has often been expressed in terms of bulk density. Many methods have been proposed for measurement of this property; some are very old, and others are relatively new. They could be classified in terms of age, but preferably they may be classified according to the principle involved. In either case, the same methods would fall into the same two general groups.

Group A. Methods requiring removal of a known volume of undisturbed soil.

1. Core methods (Coile, 1936; Curry, 1931; Kelley *et al.*, 1947; King, 1914; Lebedev, 1928; Lutz, 1944a; Lutz *et al.*, 1946; Smith, 1934; Stewart, 1943; Uhland, 1949; Veihmeyer, 1929).

2. Coated samples (Frosterus and Fraunfelder, 1926; Johnston, 1945; Miscenko, 1935; Perry, 1942; Puri *et al.*, 1934; Russell and Balcerek, 1944; Shaw, 1917; Stevenson, 1908).

3. Excavation methods (Beckett, 1928; Curry, 1931; Frear and Erb, 1920; Harland and Smith, 1928; Israelsen, 1918; Lutz, H. J., 1944b).

Group B. Methods depending on conduction of high-energy x-rays and gamma rays by soil *in situ.*

1. X-ray diffraction and absorption (Berdan and Bernhard, 1950; Watson and Jeffries, 1949).

2. Gamma ray scattering and absorption (Belcher *et al.*, 1950; Berdan and Bernhard, 1950; Bernhard and Chasek, 1953; Vomocil, 1954a,b).

1. Methods Requiring Volume and Weight Measurements (*Group A*)

The first group of methods is dependent on obtaining a known volume of soil from a profile with a minimum of disturbance of the sample taken. In the core method, a definite volume is obtained by forcing a container into the soil and thereby fllling it. In the coated

clod method, the volume of a removed sample is determined by measuring its displacement in a liquid after suitable treatment to prevent entrance of the liquid into the internal pore space. Excavation methods depend on replacing the soil removed from its natural position by some substance which will occupy the same volume as the soil removed, and the volume of which can be measured.

Parker and Jenny (1945) made bulk density measurements in a compaction study, and their data indicated the typical magnitude of the change which may be expected in bulk density as a result of packing a loam soil. The relative change in compaction was smaller when measured by the bulk density method than when a penetrometer was employed, but the coefficients of variation in the bulk density data were considerably smaller. Free *et al.* (1947) used the bulk density method to measure compaction caused by varying amounts of work done on the soil. Four soils, varying in past management and organic matter, were used. Both laboratory and field data were reported. The effect of organic matter on compactibility was striking. A Honeoye silt loam with 4.1 per cent organic matter was compacted to a maximum bulk density of 1.47 g./cm.^{3} with the Proctor technique, whereas the same soil with but 2.8 per cent organic matter was compacted to a bulk density of 1.60 g./cm.^{3} in the same apparatus and with the same technique. Similarly, a Sassafras silt loam with an organic matter content of 4.4 per cent was compacted to 1.48 g./cm.^{3}, whereas a soil of the same type with 2.6 per cent organic matter was compacted to a bulk density of 1.69 g./cm.^{3}

Weaver (1950), using a Lutz (1947) core sampler to measure the effect of traffic on bulk density of a Davidson loam, concluded that annual tractor use in itself is capable of compacting that soil to a depth of 9 inches when its moisture content is near optimum for plowing.

Weaver and Jamison (1951) used a core sampler in the determination of compaction of two soils by various loadings at several moisture contents. They concluded that soils were most compactible near the optimum moisture content for plowing, and that bulk densities of about 1.8 could be produced in a Davidson loam soil with but four passes of a loaded tractor. This is a very high density for a loam soil. Not much more compaction occurred with ten passes, indicating that perhaps even one did serious compacting.

The effects of surface compaction and crust formation on permeability to fluids is an important aspect of soil compaction. Alderfer and Robinson (1947) have indicated that compactness of the surface inch of soil drastically reduces permeability, even though the underlying soil may be quite porous and pervious. These authors used a 3.3-inch diameter core sampler for the determination of bulk densities. They reported a high correlation between the bulk density of the layer and its

noncapillary porosity. The principal compaction caused by animals in pastures on a Hagerstown clay loam and a Morrison sandy loam soil was within the surface 1 inch under sod.

The few examples given above will serve to illustrate the use of bulk density measurements in compaction studies. Compared to penetrometer measurements, bulk density data are more readily interpretable in terms of fundamental soil properties and of properties which affect plant growth. The samples removed may be used for determinations of such other properties as air space (Kummer, 1945; Page, 1947; Russell and Balcerek, 1944; Russell, M. B., 1949b), pore size distribution (Leamer and Shaw, 1941), or air permeability (De Boodt and Kirkham, 1953). However, methods depending on the removal of a sample for determination of soil volume have certain disadvantages. The methods are somewhat laborious for field use, they are unsatisfactory for stony or noncoherent samples, and unless a large core is used, most soil samples are disturbed considerably when samples are removed by this method. Baver (1956) recommended that the core diameter be at least 3 inches if compaction of the sample is to be kept to a minimum.

Jamison *et al.* (1950) made a comparison of the effects of pushing or hammering a core sampler into the soil. They concluded that the preferred method of sampling depended on the soil hardness. When a sample was easily obtained, for example, in a loose, very wet or very dry soil, pushing caused less disturbance than hammering. In compact soils, the reverse was true.

2. *Methods Using Electromagnetic Radiations* (*Group B*)

When electromagnetic energy flows through matter, its intensity is diminished. There are several mechanisms of dissipation, but these are unimportant here. The principal factor is that the diminution at some frequencies is proportional to the bulk density of the medium. The characteristics of some wave frequencies are such that their transmission is affected by few variables besides density. Their transmission is great enough so that they become suitable for practical measurement of density. X-rays and gamma rays fall into this class.

Transmission is in accordance with the Beer-Lambert law

$$\frac{I}{I_0} = ke^{-ux}$$

where I is the intensity of radiation transmitted by a thickness x, I_0 is the initial intensity, and u is the linear absorption coefficient which is the product of the absorption per unit mass (mass absorption coefficient) and the density of the medium. If one plots the log of intensity

transmitted through a constant distance from a constant intensity source against the density of the medium, a straight line is obtained if the mass absorption coefficient is constant. Radiations can be selected the mass absorption coefficients of which are very nearly independent of the chemical composition of the medium.

Watson and Jefferies (1949) suggested a method for measurement of soil compaction based on the intensity of the 1010 line of quartz in X-ray spectometry. This method works on a principle different from that of other methods employing radiation. As the soil is compacted, more crystals enter the volume in which detectable diffraction occurs, and the lines become more intense. The 1010 line of quartz was chosen because with it there was the least interference from other minerals. The authors suggested that the method can be utilized for study of compaction of field soils.

Other methods employing radiation depend on scattering and absorption, and consequently the intensity of transmitted radiation diminishes as the density increases. Berdan and Bernhard (1950) used 60-KV X-rays in a trial with two soils and found that a separate transmission curve had to be plotted for each soil. X-ray transmission was found to be sensitive to other variables in the soil. These authors suggested the use of Co^{60} gamma ray transmission for the determination of density. At the same time Belcher *et al.* (1950) proposed the use of Co^{60} gamma ray scattering and transmission for bulk density determination.

The use of Co^{60} has definite advantages. Its half-life of 5.2 years is sufficiently long so that corrections for decay are small and need to be made only about monthly. The energies of its dichromatic radiations (1.16 and 1.32 m.e.v.) are such that absorption is almost entirely by Compton scattering, and, consequently, transmission is independent of chemical composition within reasonable limits (Davisson and Evans, 1950, 1952; Siri, 1949). In addition, Co^{60} is relatively inexpensive and easy to obtain.

For gamma ray densitometry in soil, a source of gamma rays, such as a small piece of Co^{60} wire, and a detector, such as a Geiger-Mueller tube, rigidly fixed with respect to one another, are required. These may both be housed in one probe (Belcher *et al.*, 1950) or in two parallel probes (Bernhard and Chasek, 1953; Vomocil, 1954a,b).

If both are housed in one probe, gamma rays are scattered back to the probe, and some are absorbed by the intervening soil before beam intensity is measured. Hence, the mechanism is complex, but Belcher *et al.* (1950) obtained a linear relationship between the intensity at the detector and the wet bulk density of the soil. However, within a single probe the source and the detector are necessarily separated by

considerable lead shielding, and, consequently, the thickness of soil the average density of which is measured with the probe in a single position is 8 to 10 inches. In agronomy applications there is interest in thinner layers, such as plow soles. By the use of two probes this difficulty can be overcome.

Bernhard and Chasek (1953) and Vomocil (1954a,b) have suggested modifications usable in agronomic work which employ two probes and a battery-operated rate meter. The instrument is portable and, once suitably calibrated, measures wet density in the field. Its

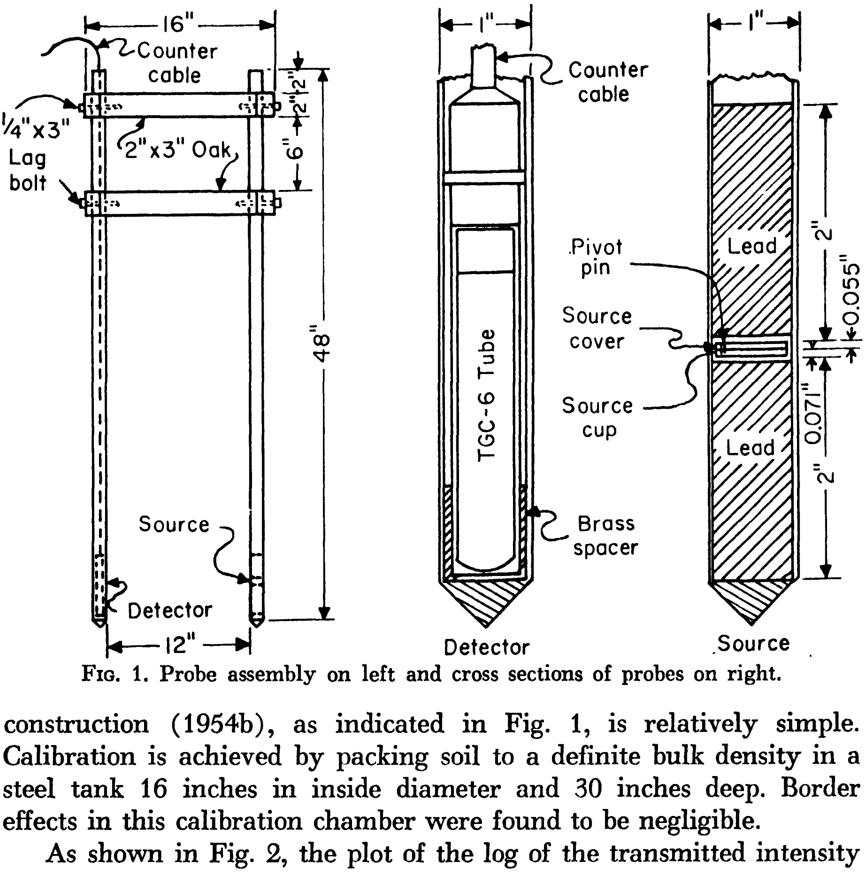

FIG. 1. Probe assembly on left and cross sections of probes on right.

construction (1954b), as indicated in Fig. 1, is relatively simple. Calibration is achieved by packing soil to a definite bulk density in a steel tank 16 inches in inside diameter and 30 inches deep. Border effects in this calibration chamber were found to be negligible.

As shown in Fig. 2, the plot of the log of the transmitted intensity (CPM) versus the wet bulk density was not linear. Deviation from linearity, probably arising from changes in geometry with change in density, does not affect the usefulness of the method. Theoretically, if no scattering or secondary emission occurred, the mass absorption coefficient for soil should be about 0.056 $cm.^2g.^{-1}$. In practice, this coefficient was found to increase from 0.023 to 0.030 as wet bulk den-

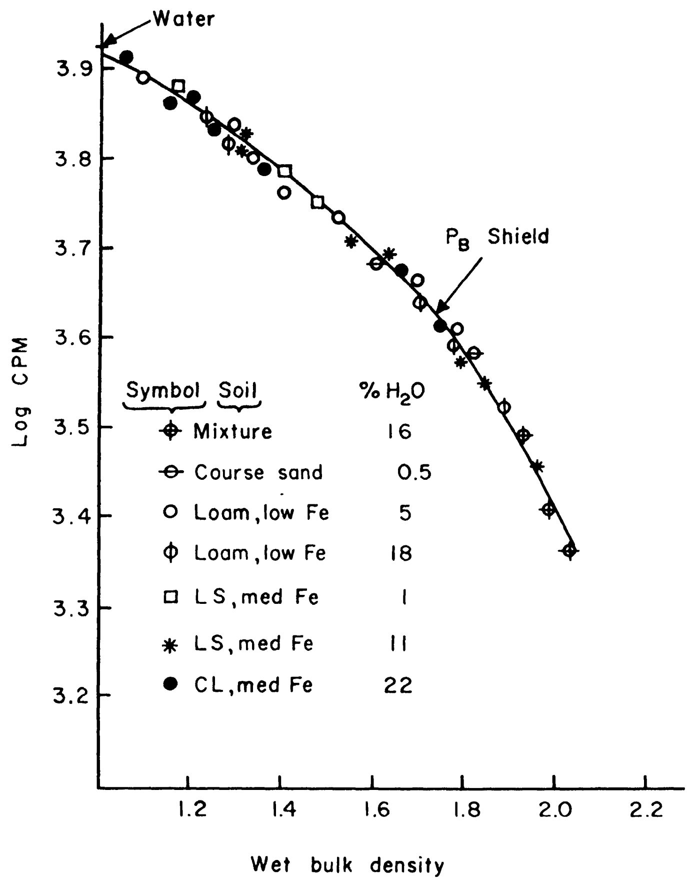

FIG. 2. Transmission of gamma rays through soil; calibration curve. Wet bulk density in g./cc.

sity increased from 1.0 to 2.0, with the distance constant at 1 foot. The difference between the actual and theoretical may have been the result of scattering and secondary emission. Bernhard and Chasek (1953) reported no change in the coefficient with density. The mass absorption coefficient for organic soils should theoretically be very nearly the same as for mineral soils.

For field use of the instrument, two holes are made in the soil into which the probes are lowered to measure the wet bulk density of the soil between them. Soil removed from these holes is saved for moisture content determination, which information is needed to convert wet bulk density into dry bulk density by the following relationship:

$$D_B = \frac{D_{BW}}{1 + M_w}$$

where D_B is the dry bulk density, DBW is the wet bulk density, and M_w is $\frac{1}{100}$ of the moisture percentage on a dry weight basis. Since the holes for the two probes must be parallel and a fixed distance apart, a guide, described elsewhere (Vomocil, 1954b), is used to prepare them. Figure 1 shows details of the instrument as used in the field.

As the radioisotope decays, I_0 changes slightly with time, and the rate meter batteries weaken, necessitating periodic recalibration. This is easily accomplished by using two fixed points on the curve; for example, water with a density of 1.00 and the lead shield used to protect personnel from radiation hazard, which has an attenuation equivalent to a wet bulk density of 1.72. The position of the entire calibration curve is shifted according to changes in counting rates for these points each month.

For an interprobe distance of 1 foot, 1 millicurie of Co^{60} gives a convenient counting rate range with bulk densities normally encountered in soil. This is sufficient radioactive Co to constitute a radiation hazard to personnel. The source is shielded with lead by placing lead plugs above and below it in the source probe and by mounting a spherical shield on the outside of the probe. This spherical shield serves also to support the probes at a fixed depth in the soil. The shield rests on the soil surface, and the source probe is lowered through it to the desired depth and is then clamped into position. When the probe is in the soil, the operator is shielded from the source by soil. Film badges have been regularly used by operating personnel, and in two years experience no detectable dosage was reported (Vomocil, 1954b).

The distance between the probes may be varied as desired to fit the experimental conditions. However, as the distance is increased, the source size should be increased in order to keep within a satisfactory counting range. Commercial rate meters usually have four ranges: 0 to 100, 0 to 1000, 0 to 10,000, and 0 to 100,000 c.p.m. The 0 to 10,000 c.p.m. range is probably the most convenient. The size of the source needed for any distance between source and detector can be approximated by the relationship:

$$I_0 = \frac{4\pi I x^2 e^{ux}}{Ca}$$

where I_0 is the source size, I is the desired counting rate in the same units as I_0, x is the desired distance between source and detector, C is the efficiency of the counting system ($\sim$0.01 for Geiger-Mueller tubes), a is the cross-sectional area of the active portion of the detector perpendicular to the beam, and u is the linear absorption coefficient. This relationship is not exact because u varies slightly with changes in distance, but the value of u for 1 foot may be used for approximation.

The gamma transmittancy method enables one to make bulk density measurements quite rapidly as compared to other procedures. Another advantage is that measurements may be made to considerable depths with less effort than is required for other methods. Plot disturbance is very slight; only two holes about 1 inch in diameter are left in the soil when measurement is completed. The precision of the instrument is ± 2 per cent, and results obtained with it compare favorably with those obtained with a 3-inch diameter core sampler (Vomocil, 1954b). Stones in the profile interfere in the preparation of the holes and in the interpretation of the data.

Some soil immediately surrounding the holes is, no doubt, compacted when the Veihmeyer tube is used to prepare holes for the gamma ray densitometer. The distance that the compacted area extends is probably very small when compared to the distance between the probes. Consequently the effect of the compaction on the measured density is small.

Several modifications can be made to adapt the gamma ray densitometer to a particular problem. For example, if it is necessary to measure the bulk density of relatively thin layers of soil, a detector with small physical dimensions might be used instead of the Geiger-Mueller tube. The least thickness of the layer measured, which increases as the distance between the probes increases, can be no smaller than the vertical dimension of the detector (about 2 inches for the tube used by Vomocil, 1954b). This dimension may be reduced by use of a different type of receiver, such as a scintillation detector. With this modification, the thickness of the measured layer may be further reduced by bringing the probes closer together. This, in addition to the fact that scintillation phosphors have a higher efficiency for gamma rays than Geiger-Mueller tubes, would allow appreciable reduction in the size of the source.

For studies of soil dynamics under loading, the source and detector could be lowered into permanently installed tubes and have no mechanical connection with one another. In this manner continuous measurements could be recorded while loads are applied to and removed from the soil between the two tubes.

The effects of surface compaction have been referred to and evaluated in the work of Alderfer and Robinson (1947). The difficulties associated with the use of the core sampler technique are magnified in its use for measurements on crusts. A method for evaluation of the physical condition of surface crusts and compacted layers is sorely needed. The gamma ray densitometer, as modified by Vomocil (1954b), is incapable of measuring this compactness owing to loss of scattered radiation through the surface and the averaging of trans-

mittancy through layers about 3 inches thick. However, an instrument based on scattering as well as transmission of gamma rays could conceivably be devised which would be suitable for this purpose. If a collimated beam of rays was directed toward the soil surface at an angle, the rays would be scattered back or reflected toward the surface from various limited depths. If a collimater preceded the detector, which was pointed at the soil at an angle toward the source, the detector would receive the radiation from a certain region in the soil plus any leakage through the shielding. The intensity of the detected radiation should then be a function of the bulk density of the surface soil if careful consideration is given to the overall geometry in the interpretation of the data. Such an arrangement seems theoretically possible and may be worthy of some developmental effort. However, a number of important variables, such as the distance from the source-detector system to the soil surface and parallelism between the two, would have to be carefully controlled.

IV. Interpretation of Bulk Density Measurements

Data from bulk density measurements may be reported in several ways. In compaction studies it is often desirable to evaluate compaction in terms of the changes in soil characteristics produced and the depth affected. For this purpose, density profiles, such as those shown in Fig. 3, are convenient. Layers of high density are not necessarily traffic-induced; they may occur naturally in soil profile development. When studying the effects of different treatments or management systems on changes in the density profiles it is necessary to compare only soils which would have similar density profiles when similarly treated. Figure 3 shows the presentation of data collected in this manner. These density profiles were drawn from data collected by the author on a Sassafras loam soil on which a rotation experiment had been in operation for seven years. The effect of rotating the potato crop with wheat and clover is clearly evident. The bulk densities plotted in Fig. 3 were treated as if they had been densities at a particular depth; actually they were mean densities of layers 2 or 3 inches thick. The depth plotted in Fig. 3 is the depth to the center of the layers.

In terms of plant growth, bulk density has significance in mechanical impedance to root growth (Jamison *et al.*, 1952; Lutz, J. F., 1952; Veihmeyer and Hendrickson, 1948), water availability (Heinonen, 1954), and aeration. In most cases of compaction of soils, each of these aspects may be involved to some extent. With present methods it is usually impossible to ascertain the relative significance of each of these variables on plant growth. However, as will be indicated in the follow-

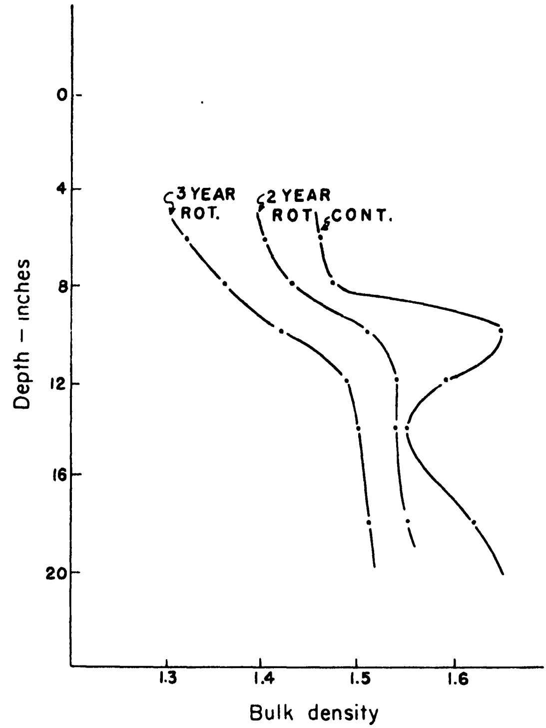

FIG. 3. Density profiles under the rows in a potato rotation experiment. Data from measurements on a study being conducted by G. D. Brill and G. R. Blake at the New Jersey Agricultural Experiment Station Farm, New Brunswick, New Jersey. Treatments consisted of continuous potatoes with a winter wheat cover crop, a two year rotation of potatoes and wheat with a clover seeding in the wheat, and a three year rotation of potatoes, wheat, and hay. Bulk density in g./cc.

ing discussion, the per cent air space at some fixed moisture content (tension) has been used with the best degree of success in evaluating soil physical conditions.

Baver and Farnsworth (1940) reported that in a Brookston clay loam in Ohio an air space of 8 per cent at the field capacity moisture content produced a relatively good yield of long tapering sugar beets. Below this air space the beets were short and stubby, and yields were sharply reduced.

Potato yields on Newmarket fine sandy loam in New Hampshire were significantly reduced when the air space was reduced to below 12 per cent, according to Dunn and Lyford (1946). These authors concluded that when both air and moisture supplies were adequate, texture had no marked effect on potato yields. Increasing air space from 14 to 21 per cent had no significant effect on potato yields. Only the in-

creases of air space in the zero to 12 per cent range were effective in increasing yields.

Kopecky (quoted by Baver, 1956) concluded that the optimum air capacity ranges for several crops were as follows: Sudan grass, 6 to 10 per cent; wheat and oats, 10 to 15 per cent; barley and sugar beets, 15 to 20 per cent. He noted that yields were reduced when the air space became too high just as when it was too low. In a greenhouse experiment Smith and Cook (1947) noted that sugar beet yields were reduced to about 10 per cent of normal when the air space was reduced to 7 per cent.

Many more data of this type are available in the literature on soils and plant nutrition. A careful review of this literature, too lengthy to be undertaken here, reveals that the correlation between crop yields and soil air space is satisfactory to make this measurement the best of those presently available.

Bulk density data can be used to calculate soil air space at field capacity if a satisfactory estimate of field capacity is available. Since both crop yields and diffusion rates of oxygen through soils (Penman, 1940a,b; Blake and Page, 1948; Buckingham, 1904; Taylor, 1949) are related, over a reasonable range, to soil air space at some fixed moisture content (ideally, field capacity), bulk density determinations provide a means for using a rapid measurement method in tilth evaluation. With soil variability being quite high, only a large accumulation of data will yield reliable information. This can be obtained only with numerous samplings, even at the cost of somewhat reduced precision and sensitivity in individual measurements.

Bulk density determinations either can be used directly in treatment comparisons or they can be converted to air space values at a preselected moisture tension for physical condition evaluation. This is especially true if a reliable rapid measurement technique and apparatus, such as the gamma ray densitometer may prove to be, is available.

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THE CONTRIBUTIONS OF STATISTICS TO AGRONOMY*

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I. Introduction

The rapid growth of statistics in the past 40 years has to quite a large, though not at all exclusive, extent been prompted by the problems raised by agronomists on methods of obtaining and interpreting data. It is therefore appropriate that a review of the contributions of statistics to agronomy should start with a classification of the inferential problems in agronomy. The subject of agronomy is so broad that any attempt at such classification is fraught with difficulties, but one it seems impossible to avoid if the broad picture is to be presented with some degree of accuracy and order.

It appears that there are three broad classes of agronomic situations in which statistics is useful, if not essential. These three classes and a breakdown of these classes into less vague topics are as follows:

A. The description and analysis of existent populations.
- *1*. The classification problem.
- *2*. The estimation of population characteristics by sampling.
- *3*. The analysis of observational data.

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B. The design and analysis of experiments.
 1. The logic of experimentation.
 2. Plot technique.
 3. Classifications of experimental material for use in experiments.
 4. The analysis of experimental data.
 5. Yield surface exploration.
 6. Long-term agricultural experiments.

C. The theory and practice of plant breeding.

This list of topics also serves as an outline of the paper.

It may be noted that class *A* involves nonexperimental populations and class *B* involves experimental populations. In the latter are included all cases in which the research worker is concerned with obtaining knowledge about treatments such as fertilizer treatments or varieties which are under the direct control of the worker. As opposed to this class is the class of nonexperimental problems dealing with the estimation of properties of existent populations, as, for instance, in estimating the proportions of different species in a plant population or in certifying a lot of seed.

All breeding problems involve the Mendelian probabilistic mechanism to a greater or less degree, and the contribution of statistics to class *C* topics has been not only with regard to the philosophy and practice of experimentation *per se* but also with regard to the mathematical and statistical theory of breeding experiments.

The aim of the present paper is not to give detailed descriptions of all these matters. Rather, it is hoped to present the broad view with references to books and papers. It will not be possible to give references to all contributors to the knowledge that will be indicated herein, and it is hoped that references at second-hand in papers and books cited will be acceptable.

Many agronomists have to deal with all the topics listed. The worker with experimental populations faces most of the problems of existent or nonexperimental populations, and the plant breeder has to use the techniques of the two previous areas as well as those entirely peculiar to genetic material. The description will therefore be stepwise in that, for example, in the section on plant breeding we shall take up only those aspects which are peculiar to the genetic mechanism, the other aspects having been covered in discussions of problems with no genetic content at all.

II. The Description and Analysis of Existent Populations

1. The Classification Problem

We are all familiar with taxonomic classifications of biological organisms. The classification problems unique to agronomy are exem-

plified by the matter of developing rules for the classifications of soils. This particular topic is beyond the depth of the author except that it is obvious to him that there are deep inferential problems involved. The topic appears to have been pursued in a rather subjective way as regards the number of different types which should be used, and the way in which the maps are drawn. The theoretical disciplines of statistics have so far not made any inroads on the general classification problem, which is that we have a population which consists of a mixture of an unknown number of sub-populations with unknown properties which we wish to break up. The reader will find an excellent biological introduction to these problems in the writings of Anderson (1949, 1954). Anderson has developed a technique by which the worker can represent five or six different attributes on a piece of paper, in such a way that he may be able to get ideas about sub-populations within the total population plotted.

We are indebted to R. A. Fisher (1936, 1938) for a solution to a classificatory problem of a different type. We are presented with observations which we *know* belong to one population and observations which we *know* belong to a second population, and we then have to decide to which of these two populations a new observation of unknown origin belongs. The procedure has come to be known as discriminant function analysis. An excellent introductory account of this is given by Goulden (1952). The extension to the case of classifying an observation as belonging to one of several populations from each of which we have a sample of observations has been treated extensively by Rao (1952).

2. *Estimation of Population Characteristics by Sampling*

In agronomic situations one is usually, but not always, concerned primarily with one characteristic of a population, namely, the mean. For example, one may have an area of corn under a certain treatment, and one wishes to obtain an estimate of the mean number of corn borers per stalk. Or one may have a pasture plot and wish to know the proportions of various species that are present. A third case of some interest is that one wishes to determine the proportion of weed seeds, viable seeds, and so on in a field or lot of grass seed.

There are essentially two types of sampling that can be used. In the one case one decides beforehand on the basis of prior knowledge the size of sample one will take, for example, the number of stalks of corn or the number of plants and leaves for a plant analysis. In the other case the problem can be tackled sequentially in the sense that the size of sample is determined by the sample observations as they arise. The theory of the latter case is well worked out only for the case of making terminal decisions, such as, for instance, the decision as to whether a

field of hybrid seed corn has been grown satisfactorily for certification, there being essentially no concern with how far above or below the certification limits the field lies but only whether the field passes a prechosen standard [for an example, see Thompson and Hutchcroft (1951)].

On fixed sample size sampling procedures there are several texts, of which we suggest to the reader, on the basis of readability for the biologist, that by Cochran (1953). No text is specifically devoted to sampling in biological problems. Most of the texts deal with the sampling of human populations, and for this reason we shall describe briefly the basic ideas of sampling theory. As regards sequential sampling the fundamental text is that of Wald (1947).

The essential idea in modern sampling is that the population must be divided, at least conceptually, into sampling units which can be listed. From this list a prechosen number of sampling units is chosen according to a random device; more precisely it must be known what the probability is that each and every sampling unit will be in the actual sample. For this reason the sampling is known as probability sampling. The reason why probability sampling has become the recognized method is that it is possible to determine from the sample the reliability of the estimates of population characteristics. To illustrate the ideas of random sampling it is worth while to consider how one would estimate the average phosphate status of the agricultural land of a region, or rather let us for definiteness say a county, because readily recognized subdivisions of a county exist. If we were concerned with a state we could take counties to be *strata*, defined to be segments of the population which are all to be represented in the sample. Within each county we could define as *primary sampling units* the townships, with the idea that we would select some townships only. Within each township we might designate sections as *secondary sampling units*, quarter-sections as *tertiary sampling units*. Finally we might define *ultimate sampling units* to be borings taken at random over the agricultural land in the quarter-sections. A sampling plan would consist of specifying that we should take t townships *at random* in each county, then s sections *at random* in each selected township, then q quarter-sections *at random* within each selected section, and finally b borings *at random* within each selected quarter-section. For simplicity we assume here that every township has the same number of sections and so on. From statistical theory we know that the variance of a county mean is, ignoring finiteness of populations, equal to

$$V = \frac{\sigma_t^2}{t} + \frac{\sigma_s^2}{ts} + \frac{\sigma_q^2}{qts} + \frac{\sigma_b^2}{bqts}$$

where σ_t^2 is the variance of true township means within the county;
σ_s^2 is the average variance between true section means within townships;
σ_q^2 is the average variance between true quarter-section means within sections; and
σ_b^2 is the average variance between borings within quarter-sections.

These variances will not in general be known. One may use informed guesses or a pilot survey to obtain an idea of their relative magnitudes. Also when one has done the sample survey the analysis of variance may be used to obtain estimates of these variances, so that the variance, V, of the county mean may be estimated. In planning the survey one would also take account of the cost of the sample in terms of t, s, q, b, say

$$C = f(t, s, q, b).$$

One would take either of two points of view: (*1*) one would have a certain amount of money C to spend and one would choose t, s, q, b, in such a way to make V as small as possible, or (*2*) one would specify beforehand what value for V is desired and one would choose t, s, q, b to make C as small as possible. These are purely mathematical problems which can be somewhat complex, but there seems no point in burdening the reader with such details [see, for example, Yates (1949a), Cochran (1953), or Sukhatme (1954)].

The example above has a structure which is very widely applicable to estimation of crop yields, soil attributes, insect prevalence, insect damage, and so on. There will in each case be unique problems of defining the types of sampling unit down to the ultimate sampling unit, and these problems are frequently not trivial. In sampling of crops for yield, for example, there is considerable difficulty in avoiding bias either from subjective placing of a square frame on a crop or from edge effects.

It is not necessary that sampling units be defined exactly but only that each distinct element in the population have a known probability of entering the sample. In general these probabilities need not be equal, and if they are not equal the appropriate estimation procedure in all cases is to add up the products of sample values and reciprocals of probabilities of selection. There are many unsolved problems in connection with the use of unequal probabilities. An example of sampling methodology with unequal probabilities dealing with estimating the yield of orange trees is given by Jessen (1955). The general idea should be readily apparent.

Before leaving the subject of sampling it is necessary to say some-

thing about systematic sampling, that is, sampling in a regular non-random way. There are two types of systematic sample which may be illustrated by the somewhat artificial problem of estimating the length along a geographical line which is planted to soybeans. One procedure would be to observe the proportion in small areas at equal distances along the line, the starting point being chosen arbitrarily (not at random). This would be a pure systematic sample. Statistical theory provides *no* means of assessing the accuracy of conclusions drawn from such a sample. Another procedure would be to divide the total length into intervals of equal length, choose a random point in the first interval, and then take observations at points along the band separated by the interval length. This is a systematic sample in a colloquial sense, but preferably is to be regarded as a single random sample of special structure, namely, that it consists of parts separated by the interval length. Such a random systematic sample is unbiased, but in spite of extensive endeavors theoretical statistics has not managed to obtain a procedure for internally estimating its reliability.

Before leaving the problem of sampling it should be noted that many problems which we may meet under another name fall in this general area, such as bacteriological counting, which has considerable importance in understanding soil-nutrient-crop relationships. In this case aliquots taken out for dilution are primary sampling units, secondary sampling units, and so on, and the total error of an estimate depends on components of variability arising at each stage in the sampling.

3. *Analysis of Observational Data*

The analysis of observational data must of necessity be based entirely on assumptions about the origin of the data. The common assumption about continuous data, as opposed to discrete data such as frequencies, is that they arise from a normal distribution. This assumption usually leads to definite unique optimal statistical evaluatory procedures, at least for simple problems, and this is undoubtedly the reason that the assumption is so popular. A large battery of statistical techniques is available when this assumption can be made, and these are covered fairly exhaustively in the standard texts on statistical methods, such as Fisher (1925b and succeeding editions), Snedecor (1937 and succeeding editions), and Goulden (1939 and 1952). The outstanding developments in statistical techniques relate to the accuracy and comparison of means and the evolution of the test of significance. Following these are the procedures of correlation and regression and the analysis of variance. The chapter headings of Snedecor's *Statistical Methods* (1956) give an excellent idea of the progression of

ideas. For frequency data and counts in general a similar battery of techniques have been developed.

One aspect of the analysis of data is the analysis of causality. The writer believes that in the application of statistics to agronomic situations much too little attention has been given to the problem of inducing causality from a set of observational or experimental data. The impression has been quite prevalent that correlation is purely a measure of association (which is true), and that regression analysis tells us something about causation (which is frequently false). This latter notion is due in part to the elementary textbook statements of the type "The regression coefficient b_1 in the equation

$$y = a + b_1x_1 + b_2x_2$$

gives the effect of changing x_1 by one unit on the attribute y." Almost any experimental scientist would interpret this to mean "If I had a situation with yield, say, y_0 and I could increase x_1 by one unit I would obtain a yield $y_0 + b_1$." This is the sort of experimental inference which unfortunately cannot be made in many situations. A prime example of this is the use of the analysis of covariance, which proceeds in the same statistical way, to answer the question "I observed yield y_1 with treatment 1 and a plant density p_1 with this treatment; also with treatment 2, I observed y_2 and p_2. What would I have observed for treatment 2 if the plant density had been p_1?"

The purpose here is not to answer this question, which is in fact unanswerable as it stands, but merely to point out that routine application of easy statistical tools does not necessarily lead to a good logical interpretation of data. My own knowledge of the difficulties in this type of inference are based very largely on the writings of Sewall Wright (1921, 1934, 1954) on correlation and causation. Wright's contribution to this aspect of scientific inference is considerable, and it is to be hoped that his ideas will achieve more general recognition.

III. The Design and Analysis of Experiments

1. *The Logic of Experimentation*

The logic of experimentation was first developed by R. A. Fisher in 1926 in a paper entitled, "The Arrangement of Field Experiments" in the *Journal of the Ministry of Agriculture*, London. The philosophy of experimentation presented therein and in the book *The Design of Experiments* (1935) has now apparently entirely permeated agronomic experimentation, and many texts which discuss the matter in detail are available (Snedecor, 1937 and succeeding editions; Goulden, 1939, 1952;

Cochran and Cox, 1951; Kempthorne, 1952; Finney, 1955; Federer, 1955).

The logical requirements of an experiment can be stated as follows:

1. The experiment should give unbiased estimates of differences of treatments that are being examined.

2. The experiment should provide within itself the means by which the accuracy of conclusions drawn therefrom can be assessed.

3. The experiment should lead to as high accuracy as possible with the resources that are available.

There are, of course, other requirements such as that the experiment be relevant to the questions at issue, but these have been recognized from the early days of experimentation.

To meet the three logical requirements set out above Fisher specified three basic ingredients of a valid experiment:

1. Randomization: This ensures unbiased estimation of treatment differences or comparisons under all circumstances.

2. Replication: This ensures the possibility of estimation of error of estimates at least under some assumptions which are not unduly restrictive.

3. Local control: This enables the experimenter to make use of likeness existing in experimental material so that gross variability in this material is not permitted to contribute error to treatment comparisons.

Under certain assumptions, particularly absence of interaction of treatment and experimental material, randomization and replication further ensure unbiased estimation of the variance of treatment comparisons and the validity of the test of significance of treatments. The author could at best paraphrase the writing of Fisher (1926), and there seems little point in so doing. Even after 31 years this paper is the best account of basic ideas that exists, and contains an excellent discussion of the defects of the use of systematic (nonrandom) designs. This particular matter has been a subject of considerable controversy, particularly in the latter 30's, and if the reader should care to study this controversy the important references are Fisher (1935 and succeeding editions), Student (1936), Barbacki and Fisher (1936), and Yates (1938). A partial case for the use of systematic designs combined with random permutation of treatments can be made when the experimenter wishes to obtain as good estimates as possible and is not concerned at all with estimating the reliability of the estimates, as may happen in routine breeding tests. If one is testing a set of varieties over an area consisting of a population of locations, it is possibly reasonable to use a random systematic design for the evaluation of treatments at each location. Even in this case, however, one would be likely to be concerned with

the magnitude of the treatment-location interactions and this cannot be assessed with systematic designs. It seems to the author to be pure opportunism to use a statistical analysis developed specifically for a randomized design for the analysis of a systematic design, as appears to have been done with systematic Latin Square designs, for example.

2. *Plot Technique*

The basic element of agronomic experimentation is plot technique, that is, the choice of size and shape of plot and of size of borders to be discarded. The topic has been examined from a theoretical point of view by Smith (1938), who developed the empirical law

$$V_x = \frac{V_1}{x^k},$$

where V_x is the variance *per unit area* with plots of size x units and k is a constant particular to the experimental conditions. The determination of optimum size and shape of plot has been worked on extensively for the case of corn breeding experiments, and the optimum size in Iowa, for instance, appears to be 2×5 or 1×10 hills. Some work on corn trials was done by Bryan (1933) and Zuber (1942) and on bromegrass trials by Wassom and Kalton (1953). There appear to be many cases for which this aspect has not been given sufficient consideration. In the 1920's and early 1930's there was extensive work on border effects which would be beyond the scope of the present paper to review. An excellent description on this topic was given by Leonard and Clark (1939).

There are uniquely difficult problems of plot technique in pasture experiments. A definitive introduction to these is given by the Pasture Improvement Committee of the American Society of Agronomy (1952).

The agronomist is plagued by the problem of the variable number of plants in the plots of his experiment. A decision has to be made at the outset as to whether or not the variability in plant number is due to the treatments. If the experimenter is not confident that the variability in plant number is not due to the imposed treatments or varieties, he must take the position that there are at least two relevant measurements, the yield of each plot and the plant number of each plot. If he is solely interested in yield then he should analyze yield as observed and unadjusted in any way. If, however, he is interested in the causal relationships between treatment, plant number, and yield, no easy technique is available. Under many circumstances the experimenter may be able to assume that the variability in plant number is purely

environmental, and there are then two alternatives available, one statistical and one biological. The statistical technique is to use the analysis of covariance and to adjust the yields for the variations in plant number. This technique is described in many texts, but its validity seems not entirely settled at the present time. It is, *inter alia*, based on assumptions which may not be realistic and also makes analysis of data more complicated. For these and other reasons a biological procedure which can be followed in many cases is to fill in the places where plants have died with other plants which are chosen so as to present a normal competitive situation and then to work with the mean of the original plants which survive or to overplant and thin to constant density. This procedure can be followed only where the number of plants per plot is designated prior to planting and cannot be used for broadcast crops.

3. *Classification of Experimental Material*

The total error of an observation for a treatment in a field experiment consists of distinct components with different properties:

a. Plot error, arising from the fact that the treatment fell on one plot of a set of possible plots rather than another plot of the set.

b. Treatment error, arising from the fact that the experimenter can never duplicate exactly the application of a treatment such as 40 pounds nitrogen per acre.

c. Observational error, arising from errors of weighing produce, or, in a cattle feeding experiment, errors of weighing and fill in determining gain, or errors arising from the sampling of each plot for yield or whatever characteristics are under study.

d. Other errors which arise and are not put under statistical control by randomization; a possible case is that the state of the plots varies systematically with time and the treatments are not applied (as would be usual) in random order.

In most agronomic experiments the important error is the plot error, the magnitude of other errors being relatively small. There are of course many exceptions to this, particularly with regard to observational error.

For cases in which plot error is important it is desirable or even essential to determine ways of minimizing its effects. The basic method of so doing is to classify or stratify the plots in blocks and to randomize the association of treatments and plots in such a way that every treatment occurs in every block. As a result additive block differences are not permitted to contribute to the error of treatment comparisons. This design is known as a complete randomized block design and with t

treatments requires blocks of t plots. If one is worried about interactions of blocks and treatments, and the blocks one uses are not such that they can be regarded as a random sample of a large population of possible blocks, as appears to the author to be the case generally, one should make up blocks so that each treatment can be represented twice in each block. This enables assessment of the data for the existence of block-treatment interactions (Wilk, 1955).

There are many cases in which one wishes to compare t treatments and Nature presents the experimenter with blocks of less than t plots. For example, a plot may be half of a leaf, the two halves of a leaf comprising the block. Or we may have 100 varieties to compare, and we know that any blocking of the experimental area into blocks of 100 plots will not result in removal of appreciable plot variability to between-block differences. A tremendous amount of research has been done by statisticians, starting with Yates (1936, and other papers), on incomplete block designs. The standard incomplete block design has the following basic properties:

a. There are t treatments to be compared by means of b blocks each of k plots.

b. Each treatment is to occur once or not at all in any one block.

c. Each treatment is to be represented r times in all in the complete plan.

The reader may consult the books of Cochran and Cox (1950), Kempthorne (1952), and Federer (1955) for designs for most practical situations. We shall here merely give a broad classification of ordinary incomplete block designs:

a. Balanced incomplete block designs, in which every pair of treatments is represented in a fixed number of blocks: for instance, with 5 treatments (a, b, c, d, e) and blocks of 3 plots a plan is

d	d	a	e	b	d	a	c	c	b
a	e	b	c	e	b	e	a	e	c
c	b	d	d	a	c	d	b	a	e

b. Quasifactorial or lattice designs, in which the number of treatments is expressible as k^n (e.g., $169 = 13^2$) and a design is obtained by setting up a factorial correspondence between the k^n treatments and the combinations of n pseudo-factors each with k levels that would arise in a factorial experiment. This leads to designs such as the simple lattice (2 replicates, k^2 treatments in blocks of k plots), triple lattice (3 replicates, k^2 treatments in blocks of k plots), quadruple lattice (4

replicates, k^2 treatments in blocks of k plots), etc., the cubic lattice (3 replicates, k^3 treatments in blocks of k plots), and so on.

c. Rectangular lattice designs, in which the number of treatments is expressible as $k(k-1)$ and the size of the block is $(k-1)$, for example, 30 treatments in blocks of 5.

d. Partially balanced incomplete block designs, which deal with the general case and contain all designs of classes (*a*) and (*b*) and some of class (*c*) as special cases. The specifications of these designs, due to Bose and Nair (1939), are rather tedious from the agronomic point of view. They are given in a book by Kempthorne (1952), as well as in other prior, less available sources.

The case of incomplete block designs occurs when the experimenter can make up a classification of plots, or experimental material, into blocks and plots within blocks. One may have in addition a classification of blocks into groups of blocks, but this is generally by the way as regards basic considerations. A second case of rather common occurrence is that the plots can be classified according to two criteria which we may designate as row and column without prejudice. Row may correspond to geographical position of a plot of land along one axis and column to position along an axis perpendicular to the row axis; or we may have a rectangular array of pot positions in a greenhouse. Another case would be where row corresponds to plant and column to branch numbered from the bottom or top. All these cases may be included under the generic term, double stratification.

Just as it will frequently be advantageous to use a single stratification of experimental units or plots in the comparison of treatments, so it will often be advantageous to utilize the double stratification. There are three main cases.

1. The Latin Square, in which there is a $k \times k$ array of plots and k treatments to be compared. The treatments are assigned to the plots according to a random one of the totality of possible $k \times k$ Latin Squares. For example, with 4 treatments the field plan may be as follows:

B	D	A	C
D	C	B	A
A	B	C	D
C	A	D	B

2. The incomplete Latin Square or Youden Square, in which there is an array of k rows with t columns of experimental units ($t > k$) and t treatments are to be compared. The plan is random, subject to the restrictions that every row contains every treatment and that the

columns regarded as blocks comprise a balanced incomplete block design.

3. The lattice square in which there are a number of $k \times k$ arrays of plots and k^2 treatments, or varieties, to be compared. The number of replicates must be at least 2 and can take any greater value, though some values lead to designs easier to analyze than others.

4. The incomplete Latin Square in which the columns regarded as blocks comprise a partially balanced incomplete block design rather than a balanced incomplete block design.

5. Designs for comparing $k \times l$ treatments with $k \times l$ arrays of plots, as, for instance, in the case of a 2-factor experiment in which levels of 1 factor are applied by rows and of the other, by columns.

The simplest case of other stratification of plots not already discussed is that of the ordinary split-plot design in which there are replicates, whole plots within replicates, and split-plots within whole-plots. This corresponds closely to incomplete block designs arranged in replicates with blocks (equals whole-plots) within replicates and plots (equals split-plots) within blocks. As continuations of the same general idea we have the arrangement of plots in split-split-plot experiments, $(\text{split})^3$-plot experiments, and so on.

One can also visualize cases in which the experimental material is divided by a square (or rectangular) array into blocks (plots) and blocks (plots) are divided into plots (split-plots) and so on.

The number of possible designs is large and the utilization of designs falls essentially into two cases:

a. The experimenter is working with material which has a natural structure.

b. The experimenter can impose any structure he wishes on the available material.

In the former case the experimenter and statistician have to decide whether the former will use the natural structure or not, basing their decision on prior knowledge about the possible gains and losses which will result. In the latter case the experimenter with the statistician has to decide what sort of structure he will superimpose on the experimental material. If, for instance, he is comparing 81 varieties in a field trial he may use one of the following:

1. Replicates of 81 plots.

2. Replicates of 81 plots with 9 blocks of 9 plots per replicate.

3. Replicates of 81 plots with 27 blocks of 3 plots per replicate.

4. Replicates of 81 plots each arranged in a 9×9 array of plots, and so on.

In any one case the number of possibilities is very large. The role of the statistician is to carry in his mind, or possibly in a catalogue, all the possible designs, and to know how the possibilities may be compared in the light of whatever knowledge of variability of material (e.g., land) the experimenter possesses, and in the light of the experience of both the experimenter and the statistician. It does not seem appropriate here to go into technical details because they are readily available in texts (e.g., Cochran and Cox, 1950; Kempthorne, 1952; Federer, 1955).

4. Analysis of Experimental Data

In addition to analytical techniques for observational or nonexperimental data, there have been considerable developments of statistical procedures for analysis of experimental data. In particular the analysis of variance has been developed extensively in the last 30 years or so to the extent of formal recognition of components of variance and components of variation in all situations involving comparative experiments. An extensive account of this as developed along a particular line for randomized experiments is given by Wilk and Kempthorne (1956). The aim of much of the work that has been done is to clarify the answer to the questions: (*a*) Does the experiment provide a proper error term for the assessment of particular effects? and (*b*) What is the estimate of the proper error? These questions occur crucially in the analysis of groups of experiments, arising by repetition of an experiment over locations and years, when, for instance, the proper error term for assessing treatments averaged over all locations and all years is a composite of some of the interaction mean squares. A rather naïve account of this, but perhaps one of the best available, is given by Kempthorne (1952, Chapter 28). The early work in this type of problem was done by Yates and Cochran (1938).

There is without doubt a strong tendency at the present time, and for the past 15 or so years, to regard the analysis of variance and tests of significance as the beginning and the end of the evaluation of an experiment. It is true that in many simpler cases one's needs are satisfied with estimates and estimates of error of estimates. There is, however, a multitude of problems for which more is clearly required. One type of problem which will be discussed in this section is what can be termed the assay problem. Another type, extensive both with respect to design and analysis, is what is termed the yield surface exploration problem, and this is discussed in a separate section.

One of the primary problems of soil scientists is to assess the relative values of various treatments given in graded doses. How, for in-

stance, does rock phosphate compare with superphosphate for the nutrition of corn? These are primarily questions of what is now called biological assay or bioassay. The situation is represented in Figure 1. It has long been known in bioassay that the important way to examine a situation like this is to consider the relative amounts of the nutrients necessary to achieve the same level of yield and not to consider the relative yields of the two nutrients at the same level of application. A

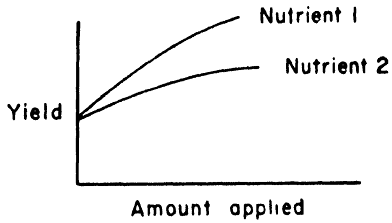

FIG. 1. Relationship of yield to amount of nutrient applied for two nutrients.

start on problems of this sort has been made by Black *et al.* (1956) and White *et al.* (1956) on the availability of phosphate in different sources.

5. *Yield Surface Exploration*

In any experimental situation the experimenter wishes to determine how the yield, which may be output of crop or amount of sodium in leaves or any attribute of interest, is related to various inputs of interest. For example, one may wish to compare varieties, in which case varieties are the inputs. One may wish to determine how the yield of oats, say, is affected by variations in the amounts of N, P, K, Mg, or B applied. In all cases we envisage yield as being determined by inputs or applied stimuli. The yield in relation to the inputs is called the yield surface. If one was considering the effect of nitrogen on kernel yield of oats one would envisage a graph of yield against amount of nitrogren applied, and the resulting curve is called the yield surface. With 2 factors, such as amount of N and amount of P, one can visualize a two-dimensional surface, representing yield for each possible amount of N and amount of P applied. The various possible classes of inputs or stimuli are called factors; thus if one was investigating the effects of N and P on yield one would have two factors, namely, N and P. The "amounts" of a factor are called the levels of the factor.

The factors which arise in all experiments are of two types. One type of factor, exemplified by variety, is characterized by the absence

of a linear ordering of the levels, and these are called qualitative factors. The second type of factor, exemplified by application of N, is characterized by the existence of a continuous set of possibilities and is called quantitative. In either case in an experiment we may have, say, 3 levels designated by 1, 2, 3, but in the former case the level 1.5 is meaningless, whereas in the latter case it means something definite, such as 60 lb. N per acre, if levels 1 and 2 correspond, respectively, to 40 and 80 lb. of N per acre.

The general problem of characterizing the yield surface, that is, the relation between yields and inputs, is now called yield surface exploration. The experimenter may be in one of two possible positions. He may wish to obtain a general picture of the yield surface, or he may wish to determine the sets of inputs which give maximum yield. It is at this point interesting to note that essentially all the methodology of experimental statistics was developed by statisticians whose main job has been to help biological and agricultural research workers, and since these workers in the technological aspects of their work have been concerned with making recommendations to a large number of small enterprises in varying circumstances, essentially all experimental designs have been aimed at general surface exploration. In recent years when large process industries have started to use statisticians in their experimental programs we have seen spirited attacks on the problems of locating optimum conditions, that is, of determination of the sets of inputs which result in maximum yield, or of course minimum yield, if that should be desirable.

The general procedure developed by Fisher and Yates for general surface exploration is that of factorial experimentation. This has come to be regarded as a statistical device, presumably because it has been developed by statisticians, but it is entirely mathematical in content, with, of course, statistical techniques to take care of "error." The reader is referred to Fisher's *Design of Experiments* (1935) and Yates (1937) for the best introductory accounts of the principle of factorial experimentation. We shall here give an account from a slightly different point of view.

It is easiest to describe factorial experimentation if the factors are all qualitative. For instance, we may have 5 varieties of wheat (v_1, v_2, v_3, v_4, v_5), 2 ways of planting (p_1, p_2), 2 types of fertilizer placement (f_1, f_2). Then a factorial experiment on these 3 factors would consist of a replicated experiment on the 20 ($= 5 \times 2 \times 2$) different combinations of the levels of the factors. The basic idea behind factorial experiment is that of interaction, and at the risk of boring the reader this will be explained. Consider the 4 combinations of 2 levels of each of 2 factors in a 2×2 table thus:

	p_1	p_2
v_1	v_1p_1	v_1p_2
v_2	v_2p_1	v_2p_2

Use the symbols v_1p_1, v_1p_2, v_2p_1, v_2p_2 to represent the *yields* of the 4 combinations. Then the effect of p_2 versus p_1 is

$$v_1p_2 - v_1p_1 \text{ at level } v_1 \text{ of factor } v;$$
$$v_2p_2 - v_2p_1 \text{ at level } v_2 \text{ of factor } v.$$

If these two simple effects are equal, then the factors are said to have no interaction at these levels. To extend the concept to 5 levels of one factor and 3 levels of another factor one could look at all the 30 possible 2×2 tables within the 5×5 table. If at least one of these 2×2 tables shows interaction, then the two factors are said to "interact." It has not been emphasized sufficiently in the literature that one cannot talk about two factors interacting or not interacting without specifying the scale of measurement. Consider, for instance, the two following tables.

yield

	p_1	p_2
v_1	10	20
v_2	20	40

$\log_{10}$ yield

	p_1	p_2
v_1	1.0	1.3
v_2	1.3	1.6

In the left-hand table there is interaction measured by

$$\tfrac{1}{2}\,|\,(v_2p_2 - v_2p_1) - (v_1p_2 - v_1p_1)\,| = 5$$

(the divisor $\tfrac{1}{2}$ is put in by convention), and in the right hand table the measure of interaction is

$$\tfrac{1}{2}\,|\,(1.6 - 1.3) - (1.3 - 1.0)\,| = 0.$$

Thus the two factors interact with regard to yield but *not* with regard to log yield. The fact that the farmer is interested in yield and not in log yield, for instance, appears to the present author as an inadequate excuse for not looking for that function of yield which results in easy representation of effects, as occurs if there are no interactions. One wonders how often experimenters have chased notions like an NP in-

teraction as regards yield when there would be no interaction as regards log yield (or the reciprocal of yield).

R. A. Fisher is responsible for the basic notion of interaction presented above, and this is one of his many great contributions to the theory of experimental inference. It is curious that so primitive a notion should have been precisely formulated so late in the history of experimentation. In presenting the philosophy of experimentation Fisher gives two steps:

1. Experimentation with one factor at a time.

2. Recognition of the possibility of interactions and hence factorial experimentation and rejection of experimentation with one factor at a time.

The present author regards a third step as essential for completeness:

3. The removal of interaction by choice of scale of observation if possible.

To exemplify this step, let us assume that as a reasonable approximation the Mitscherlich law holds, so that yield in terms of n, p, and k, the amounts of N, P, and K added, is

$$y = C(1 - e^{-c_1 n + b_1})(1 - e^{-c_2 p + b_2})(1 - e^{-c_3 k + b_3}).$$

Then, if adequate, a factorial experiment with say, 2 levels of each of N, P, and K will lead to a verdict, by statistical techniques given in standard texts, that there is interaction among the 3 factors. A little thought, however, shows that if one analyzed the logarithms of yield instead of the yields themselves, one would not reach the verdict that there is interaction except with a frequency appropriate to the test. The log scale would under these circumstances be best for the representation of the data. The situation as regards statistical methodology at present is that we are well equipped to study the possible existence of interactions but are badly in need of developments which will aid step (*3*) added above.

In the case of quantitative factors we have to envisage what may be termed a factor space, which is a geometrical representation of the total set of factor level combinations which is of interest to the experimenter. In the case of the crop nutrients N and P and corn yield, for instance, we can possibly envisage the factor space as the totality of points in the region R (see Fig. 2). The particular boundaries of the region R will be based on the prior knowledge of the experimenter and/or on the experimenter's aims. He may wish to investigate the region up to 200 lb. of N and 100 lb. of P per acre, for example. Let us take this latter case for purposes of discussion. Just what the experimenter should do is a moot point, and it is to be hoped that statisticians will in the near future pro-

duce some objective procedures. What the author does is to go through a subjective evaluation of the relative importance of the two factors as judged by the relative changes to be expected along lines parallel to each axis: e.g., if along lines of constant N the greatest range of yield is expected to be from a minimum of 50 to a maximum of 100, and along constant P lines the greatest range in yield is expected to be from 40 to 120, then he would say that one should probably have 3 levels of N for every 2 levels of P. The total number of combinations would be that multiple of 6 which is within the resources of the experimenter, subject to the condition that each combination should be represented twice. This might lead to 6 levels of N and 4 levels of P, though the author might

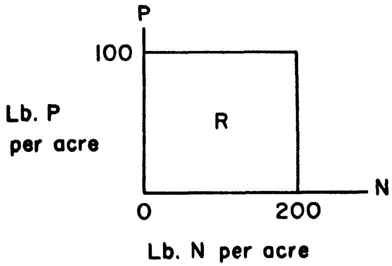

FIG. 2. A simple example of a factor space.

change these numbers if blocking were essential. Having chosen the number of levels the author would determine the position of the levels on the following sort of subjective basis:

1. If the yield is expected to be linearly related to dose, he would have the levels spaced equally from the beginning to the end of the interval, or probably clustered at the ends of the interval with a few in the middle.

2. If the yield is expected to relate linearly approximately to the logarithm of dose, he would use equal intervals along the log scale with a dose of zero.

3. If it were expected that the yield would exhibit a hump in the middle of the range somewhere, he would use doses spaced equally on the arithmetic scale.

In closing it must be reiterated that these are the author's personal opinions not put up for or susceptible at present to logical examination.

In the case of qualitative factors, the factor space consists of a grid or lattice of points without a distance being defined along any axis. With the early formulation of the principle of factorial experimentation one has no recourse but to obtain an observation at each point of the lattice.

What is said above about either qualitative or quantitative factors is well as far as it goes, but, colloquially speaking, it does not go far. It would be absurd to tell an experimenter with 6 factors, say, that he should perform a $3 \times 4 \times 5 \times 3 \times 2 \times 5$ factorial experiment, the designation meaning that the first factor is to be used with 3 levels, the second with 4 levels, and so on. This would involve him in testing 1800 different treatment combinations. What is needed here is a matter of statistical and experimental concern.

It appears that one can divide problems of general yield surface exploration roughly into two categories:

1. The experimenter has a large number of factors, say 6 or more, which he thinks may have some effect on the yield and wishes to know which of these are important.

2. The experimenter has a number of factors which he knows on the basis of prior experimentation or information to be important and wishes to characterize the yield surface.

For the former category of problems statisticians have devised a procedure called fractional replication. This procedure is based on prior knowledge or merely on the hope that high-order interactions among factors tend to be small, and consists of selection of a fraction of the total number of possible treatment combinations which enables the estimation of main effects and low-order interactions, not defined herein. The assumptions are not unwarrantably unrealistic when it is realized that an interaction of k factors involves the k^{th} order mixed derivative and higher order derivatives only, when the factors are quantitative, or are qualitative but have an underlying quantitative nature. In the case of 5 factors each at 2 levels each one can, for instance, estimate main effects and 2-factor interactions from 16 ($= 2^4$) or one-half of the 32 ($= 2^5$) treatment combinations. In the case of 6 factors at 2 levels each, one can use a one-half replicate involving 32 treatment combinations or plots, arranged in blocks of 16 to estimate all main effects and 2-factor interactions. It would not be appropriate to list all the possible designs, a partial specification of which is given by Kempthorne (1952). It is to be hoped that a satisfactorily complete index of the possible designs will be available in the near future. The fractional factorial designs of 2^n type are primarily suitable for discovering which factors of a set of factors are capable of producing variations of practical significance in yield or whatever is under consideration.

For the second category, which is the determination of yield surface for factors known to be of importance, it is obviously impossible to get much information by using only 2 levels for each factor, and one must go to 3, 4, or 5 levels. One immediately encounters difficulties because 4^6 is equal to 4096, and no experimenter can possibly use this number

of plots. One way out of the difficulty is to use fractional replication, but this does not take one far enough in many cases. One possible answer is to use a fractional 2^n experiment to determine a scale of measurement and/or functions of factors which result in inappreciable interactions. For instance, it is possible, though not likely, that some nutrients are important in their relative magnitudes, or that the yield of a grass mixture depends in a simple way on the total amount of seed and the relative amounts of species. If one can achieve such understanding of the problem, one can then perform experiments with just a few factors at a time with adequate replication to obtain a reasonably precise picture of the yield surface. There seems to be no generally practicable answer except one of this type.

A very interesting class of designs for this problem, called composite designs, has been developed recently by Box and Wilson (1951). These consist of a fractional 2^n factorial augmented by treatment combinations set off at equal "distances" from the "center" of the 2^n factorial design. The words "distances" and "center" are here placed in quotes because from a strictly logical point of view these concepts are unjustifiable abstractions. Notwithstanding, this type of design will probably be useful for general surface exploration.

It is possibly easy to get the view that general surface exploration is a new topic and that agronomists have not been concerned with the topic until recent years. This is undoubtedly based on the preoccupation of agronomists with the standard analyses of variance given in elementary statistical texts, but work on the problem dates from the beginnings of modern statistical methods or before (e.g., the Mitscherlich law and the resistance law). In connection with general comment on the present situation the recent work of Heady (1949) and his associates on the economic implications of yield surfaces is of relevance.

In recent years Box and Wilson (1951) and associates have worked on the problem of determining the optimum inputs of stimuli for engineering processes. In an agronomic situation the stimuli could be nutrients, seed rate, time of planting. The basic description of the methodology is given in the book edited by Davies (1954). The steps envisaged are roughly:

1. A design to enable the fitting of the surface by a plane.

2. "Walking" up the plane by the method of steepest ascent.

3. When it appears that no steady improvement is being achieved, use of a design by which the nature of the surface in the near-stationary region may be explored; suggested designs are called composite and rotatable designs which enable the fitting of a second-degree surface, that is, one which contains square and product terms in the variables.

4. Reduction of the yield surface equation to standard (canonical)

form by shifting the origin and rotating the axes. This enables one to visualize the nature of the surface in the neighborhood of the optimum.

It is the author's opinion that there are logical deficiencies in this method of attack, though if some of the steps are repeated along the way the method will lead to the optimum, if a reasonably well-defined optimum exists. It is not appropriate to go into these matters herein. The main disadvantage of this procedure in agronomic situations is its main advantage in industrial experimentation, namely, the fact that the experiment must be performed sequentially. In the general agronomic situation it seems unavoidable that the experimenter must make up a complete plan for use in a particular season, and it would not seem profitable to attempt to build up knowledge about the yield surface from some points in the factor space observed in one season and other points observed in a different season. Also it does not seem appropriate to use a lot of resources to determine the optimal inputs, say, levels of N, P, K, etc., for a particular season and location. Rather the experimenter should search for general relationships which prevail over all seasons. For these and other reasons there has not been published to the author's knowledge any agronomic examples of optimum seeking by sequential experimentation.

6. *Long-Term Agricultural Experiments*

The agronomist is very frequently faced with the problem of assessing long-term experiments, which can be of two types:

1. Perennial experiments.
2. Rotation experiments.

The perennial experiment involves no new difficulties of design as compared with the annual experiment but does involve considerable difficulties in analysis. It is perhaps worth recalling that R. A. Fisher was brought to Rothamsted Experimental Station in 1920 by E. J. Russell, the director at that time, to make sense, colloquially speaking, of the masses of experimental data accumulated in long-term experiments such as the famous Broadbalk experiment started in 1843. These experiments, though not all strictly perennial in the basic agronomic sense of the word, lead to observations on plots treated in the same way, more or less, year after year. They, therefore, lead to what we now describe as time series observations. These were the basis for the beautiful (mathematically and statistically) development by Fisher of orthogonal polynomial fitting, as exemplified in the 1921 and 1925a references. If the author was permitted to make an agronomic judgment in this connec-

tion, it would be that this line of investigation has been rather unsuccessful in adding to agronomic knowledge. There have been several applications of the methodology of Fisher to agronomic situations, particularly to the understanding of crop-weather relationships, but these do not strike this author as being at all successful agronomically. He would express the view that one of the major, if not the major, statistical problems of agronomic interest is still the development of statistical techniques for understanding, not merely representing, a series of crop yields in successive years with no variation of experimenter-imposed conditions, and the relationship of such a series to meterological series. The author regrets that he has no really fertile ideas for attacks on this problem. It may be that some of the modern work on time series will be of use, but it seems unfortunate that this modern work is devoted almost exclusively to the understanding of stationary time series, whereas the standard agronomic situation is that the series are not stationary. To put things in a possibly more illuminating way, the agronomist is as much interested in how the series progress to a stationary state as in the actual stationary state. A difficulty well recognized by researchers on time series methodology is that a series which is long agronomically speaking, for instance, as long as 50 years, is short from the point of view of determining its statistical structure. The best review available of polynomial fitting as applied to agronomic data is that of Cochran (1939).

When we turn to rotation experiments we find that there are problems both of design and analysis. As regards design the reader should consult the annual reports in the 1930's of the Rothamsted Experimental Station, the paper by Cochran (1939), and the paper by Yates (1949b). The basic idea of design is that the agronomist cannot sample seasons at a faster rate than one per year so that all phases of the rotation must be represented in each year. This is what may be termed the hard core of design principles. Some of the experiments designed at Rothamsted by Fisher in the 1930's are marvels of combinatorial magic and incorporate a variety of balance features such as that over a period of, say, 24 years every possible treatment occurs on every plot. A more recent example of the complex design is given by Yates (1949b). Methods for analysis of rotation experiments based on least squares and often using orthogonal polynomials are given in the paper of Cochran (1939). See also the paper by Patterson (1953).

One problem of design which appears to have been neglected somewhat is the starting problem. This may be illustrated with a corn-corn-oats-meadow rotation denoted by CCOM. Using the principle that each phase of the rotation is to be represented in each year one must use at least four plots as follows:

Year	Plot 1	2	3	4
1	C			
2	C	C		
3	O	C	C	
4	M	O	C	C
5	C	M	O	C
6	C	C	M	O
7	O	C	C	M
8	M	O	C	C
	.	.	.	.
	.	.	.	.

The starting problem is that of deciding what crop plot 2 is to receive in year 1, plot 3 in year 1 and in year 2, etc. The philosophy of the author is that these plots should be given agronomic treatments which as nearly as possible maintain the plots in the same state as they are at the beginning of the experiment. These treatments must be specified by the agronomist. The problem is important because the agronomist is concerned with the two distinct questions: (*1*) What is the rate of approach of the rotation to its steady value? By this we mean that if the rotation is a good one the plots which receive it will improve agronomically, and the agronomist is concerned with the rate at which the rotation brings the land up to a specified value as regards fertility level, or soil structure, or whatever is considered important. (*2*) What is the level of yield, soil structure, etc., when the rotation has been continued for a long duration? The starting problem is not of much relevance to the second question but appears to be quite crucial for the first question.

A difficulty of analysis of rotation experiments is the specification of crop and possibly soil attributes which should be considered. From the point of view of the farmer the value of a rotation must depend on the following considerations:

1. The present value (i.e., future monetary returns devalued by a standard rate of interest) of the crop yields. This idea appears to have been presented first by Rojas (1955).

2. The present value of the land, that is, the future monetary profit under a particular crop sequence devalued by a standard rate of interest.

3. Institutional factors such as the practicality of a crop sequence or set of sequences on a farm.

4. The noneconomic desires of the farmer—how he wishes to spend his life.

The farmer may also have the philosophy of wishing to maintain the land at its present status or at some desired status for his successors, but

economic pressures may prevent him from so doing. It is conceivable that a farmer could decide to use a high-profit rotation which depletes the soil for some years followed by a low-profit rotation which restores the land to a particular status. It is when the agronomist is also acting as an extension worker that questions of the above sort must be considered. Perhaps the agronomist per se should concern himself solely with the estimation of what happens with a rotation, with regard to yield of crops and soil characteristics, but this presents him with a large number of possible results which do not lead to easy condensation and agronomic conclusions. In the CCOM example the author can envisage the following attributes of the rotation: (*1*) is the rate of increase or decrease of yield of first-year corn to its steady value. (*2*) is the steady value of the yield of first-year corn. (*3*) and (*4*) correspond to (*1*) and (*2*) for second-year corn. (*5*) and (*6*) hold similarly for oats, (*7*) and (*8*) for meadow. (*9*) is the rate of increase by four-yearly intervals of the total energy yield over the four phases. (*10*) is the steady value for total energy yield over the four phases. (*11*) and (*12*) correspond to (*9*) and (*10*) for total digestible nutrients, and so on. It was with questions of this type in mind that Dutton (1951) investigated the possibility of representing the yields of a continuous crop sequence by the relationship

$$\text{Yield in year } t = A\{1 - Be^{-kt}\}.$$

For this relationship the steady value is A and the rate of approach to this steady value measured logarithmically is k.

A second difficulty in analysis is that the errors of a rotation experiment are unlikely to be uncorrelated. For example, the yield of corn following meadow will be correlated with the yield of meadow.

The reasons for mentioning these difficulties in the design and analysis of rotation experiments are firstly to indicate that naive application of the analysis of variance to rotation data, treating years as replicates, for example, is unlikely to lead to the answering of the real questions, and secondly to stimulate statistical research on the problems.

IV. Applications of Statistics to Plant Breeding

The books directed to this area are as follows. Mather's (1938) book is devoted to uses of statistics in interpreting what may be termed classical or formal genetic data as can arise if a plant breeder is studying the inheritance of regularly behaving simple genetic phenomena, such as resistance of oats to a particular rust race. Mather's (1949) book is devoted to the application of statistical considerations and techniques to the understanding of quantitative inheritance, as occurring, for instance, with the yield of corn, which is probably controlled by a large

number of gene loci. The author (Kempthorne, 1957) has written a book on the general topic of statistics as applied to genetics, most of which is applicable to any type of organism. Li's (1955) book is directed primarily to population genetics, a topic which is obviously of importance to plant breeders. The contributions of statistics to this topic consist of the following distinct parts:

1. Statistical techniques for the evaluation of formal genetic data, such as checking genetic hypotheses of the type that the inheritance of a trait is via a single factor with two alleles, one dominant to the other, or estimating the linkage between two genetic factors. In this area the great contributor has without doubt been R. A. Fisher.

2. Applications of probability theory to genetic situations, and procedures such as natural selection and inbreeding. Here the main contributors are Fisher (1930, 1949) and Wright (1921a, 1931, 1951). In each case there are other important papers too numerous to list here.

3. The mathematical theory of quantitative inheritance tracing back to Fisher (1918) and Wright (1921a).

4. The interpretation of data on quantitative inheritance, for which particular reference should be made to Fisher (1918), Mather (1949), and Wright (1951).

5. The development of experimental designs specifically for the estimation of parameters which give a useful description of quantitative inheritance. In addition to the work of Fisher and Mather already indicated above it is appropriate to mention the work of the group at North Carolina State College on average degree of dominance and of workers at Iowa State College on fairly general situations.

6. The development of selection procedures, such as reciprocal recurrent selection, which is associated with the North Carolina group.

It would not be appropriate to review these matters in detail both because they are of no particular interest to the sizable group of agronomists who are not working in applied genetics and because a lot of space would be required. The reader is referred to the books cited above, and particularly to Kempthorne (1957), which attempts to cover essentially all the aspects mentioned.

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THE RESIDUAL EFFECT OF FERTILIZER

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I. Introduction

The residual effect of fertilizer commonly refers to the favorable response of crops to the major nutrients applied to a previous crop. In addition, certain secondary and minor nutrients may remain and bring about beneficial results. Furthermore, legumes and other crop residues grown as a result of previously applied fertilizer may decompose to effect increases in the yield of currently growing crops. It is believed that residual effects of soluble nitrogen fertilizers come about largely through this means (Fig. 1).

In some cases the effect from previously applied fertilizers may actually be harmful in that soils may be made acid, an unfavorable nutrient balance may be established, or excessive quantities of secondary nutrients may be left in the soil. This latter situation is common in greenhouse soils.

As fertilizer applications are increased, in expectation of high yields, the chances of unbalance and other injurious effects increase. Furthermore, changes in fertilizer carriers are reducing the possibility of secondary nutrient benefits, or of injurious effects from secondary nutrients and accompanying ions, such as chlorides.

In this paper the writers call attention to some of these commonly disregarded effects of heavy applications of present-day high-grade fertilizers.

II. Phosphorus and Potassium Accumulation

Fertilizer recommendations in Michigan are based on soil type and the results of soil tests. Experiments have established economical rates

of application for various crops, soil types, and nutrient levels. The field experiments are still being conducted and data are still scanty for some situations. As a result, the most satisfactory grades are not always recommended and applied, and crop removal of nutrients is not always correctly gauged. As a result, nutrients sometimes accumulate. To obtain information on such nutrient accumulations many field plots have been sampled and tested for phosphorus and potassium. Iowa research workers have been following the same procedure.

FIG. 1. Barley grown after sugar beets on Sims clay loam. The two bundles at the right (3) were larger than the left two bundles (6) because alfalfa was grown on the plot three years earlier. There is no legume included in the number 6 rotation. Fertilizer is necessary for successful alfalfa production on that soil.

Residual effect from nitrogen is shown by the greater size of the left bundle in each pair. The increase was the result of 40 pounds of nitrogen applied as a side-dressing for sugar beets. Yields of the plots represented by the bundles were, left to right, 43.9, 34.2, 47.6, and 39.1 bushels per acre.

Hanway *et al.* (1953) applied P_2O_5 and K_2O at rates of 0, 60, and 120 pounds an acre, each nutrient alone and in all combinations. Recovery of applied phosphorus in the hay crop ranged from 33 to 62 per cent, whereas that of potassium ranged from 74 to 140 per cent. Soil tests showed that considerable "available" phosphorus had accumulated in the top 2 inches of soil but that soil potassium levels had not increased.

A crop sequence experiment has been in progress on Sims clay loam in Saginaw County, Michigan, for 16 years. The soil on all plots was sampled when the experiment started. Samples were taken again in

1956. Divided at the beginning, one-half of each plot received fertilizer at the rate of 200 pounds per acre per year. The other half received 80 pounds per acre each year during the first 10 years, then 400 pounds each year during the last 6 years. Thus at the time of the 1956 sampling all plots had received the same amount during the total period, namely, 3200 pounds per acre. The fertilizer grade was 4-16-8.

TABLE I

Available Soil Phosphorus, Potassium, and pH before and after 16 Years of Fertilization and Cropping

Seven cropping systems on Sims clay loam (Michigan)

	Soil constituent					
			(pounds per acre)			
	pH		P		K	
Cropping system[1]	1940	1956	1940	1956	1940	1956
1H C,SB,B,A,A	6.2	6.5	54	70	62	148
1L "	6.7	6.5	62	70	79	110
2H SB,C,B,A,A	6.8	6.4	62	72	69	114
2L "	6.5	6.4	57	74	55	121
4H C,SB,O,B,A	6.4	6.5	45	80	69	121
4L "	6.0	6.5	51	84	62	100
5H C,SB,B,A,A	6.8	6.6	55	96	83	128
5L "	6.7	6.6	66	84	96	137
6H C,SB,B,Be,W	6.8	6.9	47	96	83	128
6L "	6.8	6.9	48	96	65	128
7H C,SB,B,Be,W(GM)	6.9	6.6	57	72	62	110
7L "	6.1	6.6	47	72	55	110

[1] C = Corn, SB = Sugar Beets, B = Barley, O = Oats, Be = Beans, W = Wheat, A = Alfalfa, GM = Green Manure. All plots received 3200 pounds of 4-16-8 fertilizer an acre during the 16 years. The "L" plots received 200 pounds each year. The "H" plots received three-fourths of the fertilizer during the last 6 years. The number 5 sequence has been as indicated during only the last 6 years. Before that it included oats and clover instead of 2 years alfalfa.

The data reported in Table I show that even at these relatively low rates of fertilizer application over the 16-year period, both phosphorus and potassium levels did build up. This occurred under seven different cropping systems.

Michigan experiments have shown that in soils below pH 7 phosphorus test values under 50 and potassium test values below 150 pounds per acre should be considered low. The 1956 test results show that the phosphorus levels have risen relatively more than have the potassium levels. Such results indicate that it may be time to change the fertilizer grade to one containing a higher percentage of potash, and perhaps to one having equal amounts of phosphate and potash.

An alfalfa experiment was started in 1951 on Kalkaska sand. One of the objectives was to determine the effect of fertilizer on the longevity of the alfalfa. First 0-20-20, then 0-13-39 were applied at three rates. In 1956 the soils were tested to determine nutrient accumulation. In Michigan sandy soils having less than 50 pounds phosphorus and 150 pounds potassium, a fertilizer like 0-20-20 would be recommended for alfalfa. Where phosphorus levels, however, rise above 50 and potassium levels remain below 150, the ratio should be 1:2 with respect to the two nutrients.

The data in Table II show that where 358 pounds of P_2O_5 had been applied between 1951 and 1955, soil phosphorus levels actually had

TABLE II

The Effect of Fertilizers on the Available Phosphorus and Potassium Contents of Sandy Soil under Continued Production of Alfalfa
Kalkaska Sand (Michigan)

Pounds fertilizer applied 1951–1955 $N:P_2O_5:K_2O$	Soil tests 1956 (pounds per acre) P	K
0:0:0	24	59
0:106:158	37	91
0:252:356	43	77
0:358:514	61	104

risen sufficiently to warrant changing the recommendation to 1:2 ratio fertilizer (the available phosphorus content had risen above 50 pounds). It is interesting that the potassium levels rose less, relatively, than did the phosphorus levels. Leaching and luxury consumption of potassium by the alfalfa are probably responsible.

The Michigan Station has an extensive organic soil research farm (Fig. 2). Ratios and rates of fertilizer application, studies on time and method of application, and many crops have furnished splendid material for evaluation of nutrient accumulation. The nature of the treatments is evident from Tables III, IV, and V. Spurway methods were used in the soil tests. Organic soils were extracted with 0.018 *N* acetic acid; mineral soils, with 0.13 *N* HCl.

The behavior of organic soils differs from that of mineral soils in so far as accumulation of residual nutrients is concerned. The data in Table III show little indication that soil phosphorus levels were increasing with increased phosphate applications. Perhaps the rates were too small to expect accumulation of phosphorus extractable by the weak acid.

Soil potassium levels, on the other hand, did increase markedly with increased applications of fertilizer potash. It is interesting that the levels were lower in the spring than in the fall. This situation has been observed at other times (Table IV). Apparently potassium leaches readily during the winter and early spring. This was also indicated by an experiment in Canada.

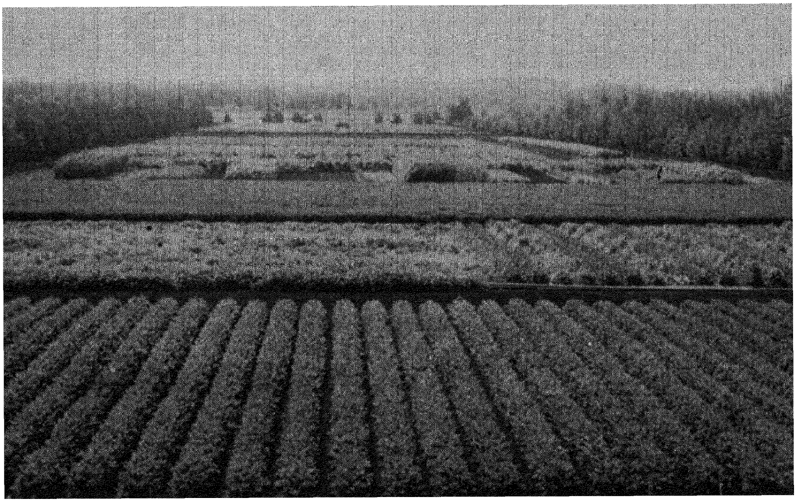

FIG. 2. Michigan State University Muck Experimental Farm. More than 70 different crops are grown regularly on this farm. Very large quantities of fertilizer have been applied on many of the plots. Soil tests now show that potassium has built up to extremely high levels. In such instances, applications may be reduced to increase fertilizer efficiency.

Filman *et al.* (1948) found that water pumped from a 5000-acre marsh near Toronto contained enough potassium to represent 17 pounds from each acre in the marsh. It seems that with organic soils one may lose considerable potassium if an attempt is made to build up soil potassium to an extremely high level.

Table I shows that potassium levels did become very high at the Michigan muck farm. Many celery growers apply a ton of fertilizer every year. Soil tests show they are applying much more than is needed. The yields given in Table V indicate that in this soil 400 pounds of K_2O was sufficient. The application of larger quantities simply left more in the soil to be lost through leaching or luxury consumption by the crops. Extremely high levels of potassium may in fact result in injuries. Magnesium deficiency in celery has been most intense on plots which received the heaviest applications of potash.

TABLE III

The Influence of Fertilizer Treatment on the Yields of Onions and the Amount of Soil Phosphorus and Potassium in Organic Soil

Fertilizer[1] (pounds/acre)	Placement	Soil tests (pounds per acre) P Fall 1951	P Spring 1952	P Spring 1953	K Fall 1951	K Spring 1952	K Spring 1953	Yields (number 50# bags) 1951	Yields (number 50# bags) 1952
400	Drilled in	14	14	11	276	265	215	162	249
400	1″ below seed	14	11	11	308	164	168	320	502
600	1″ below seed	15	16	11	339	309	207	381	499
800	1″ below seed	18	16	12	487	270	276	492	563
800	Drilled in	17	18	11	395	291	230	313	399
400 } 400 }	{ Drilled in { 1″ below seed	18	13	16	356	316	260	425	583

[1] 4-10-20 applied in the spring of 1951, 5-10-20 in 1952. Treatments were replicated 6 times. The 1952 samples were taken before the fertilizers were applied.

TABLE IV

The Influence of Fertilizer Treatment on the Yields of Onions and the Amount of Soil Phosphorus and Potassium in Organic Soil

$N:P_2O_5:K_2O$[1]	Soil tests (pounds per acre) P Sept. 1953	P May 1954	K Sept. 1953	K May 1954	Yields (50# bags per acre) 1953	Yields (50# bags per acre) 1954
0:200:100	21	18	282	171	1130	785
50:200:100	21	23	296	187	1134	811
0:200:100	27	21	301	236	1060	776
50:200:200	20	22	276	267	1101	782
0:200:300	20	23	375	302	1057	728
50:200:300	26	20	357	264	1085	748

[1] Pounds per acre, applied each of the years 1952, 1953, and 1954.

Experiments have shown that high levels of soil potassium may eliminate the response of certain crops to sodium. Depending upon the crop and the value of labor this may have economic significance because sodium chloride is plentiful and cheap in Michigan. The data in Table VI show that 500 pounds of salt (NaCl) caused an increase in yield of over 2 tons of sugar beets per acre where the fertilizer contained a low percentage of potash but did not increase yields where 0-10-60 had

TABLE V

The Influence of Fertilizer Treatment on the Yield of Celery and the Amount of Soil Phosphorus and Potassium in Organic Soil

$N:P_2O_5:K_2O$ (lb./acre)	Soil test (pounds per acre) P May	P Sept.	K May	K Sept.	Yields (tons per acre) 1953	1954
50:200:0	29	33	231	157	49.6	46.5
50:200:400	33	33	232	502	53.3	51.9
50:200:800	39	45	768	698	50.5	60.0
50:200:1200	39	47	1005	1267	46.8	57.2

TABLE VI

The Effect of Potash and Salt (NaCl) on Sugar Beet Yields on Organic Soil

Grade of Fertilizer[1]	Tons per acre: No salt	Tons per acre: 500 lb. salt/acre
0-10-10	13.8	16.0
0-10-20	18.7	21.7
0-10-30	20.7	22.3
0-10-60	23.5	23.0

[1] 1000 lb. per acre.

been applied. The grower, of course, must decide whether he can afford the salt application to save the higher cost of the extra potash.

A quotation from Pesek and Dumenil (1956) of Iowa summarizes fairly well the writers' thinking regarding residual nutrients from heavy and perhaps improperly balanced fertilizer applications. "A good soil test will measure the residual from several years of heavy fertilization, especially in the case of phosphate. It is well for a farmer to keep up-to-date on the fertility status of his soil. In this way he will be able to plan and follow an economically sound fertilization program for his farm which includes taking full advantage of the extra dividends from fertilizer carryover."

It is especially important that organic soils be regularly tested. Fertilizer recommendations for crops grown on these soils in Michigan are being based almost entirely on soil test results (Table VII).

III. Secondary and Minor Nutrients

Fertilizer technology has changed much during recent years. Demands for high grades of dry fertilizers and an urge to save labor by

TABLE VII

P_2O_5 Recommendations for Crops to Be Grown on Organic Soils in Michigan

Available P in soil (Lb./acre)				P_2O_5 recommended
			4	250
			7	200
		1	10	175
		4	13	150
	1	7	16	125
1	4	10	20	100
4	8	13	24	80
8	12	16	28	60
12	16	20	32	40
16	20	25	36	20
20	25	30	40	0
Grass Wheat Clover Corn Oats Soybeans	S. beets Mint Beans Carrots Cucumbers Alfalfa	Potatoes Peas Spinach T. beets Asparagus Tomatoes	Celery Onions Cauliflower	

using solutions, which may be pumped and sprayed, have resulted in marked changes in carriers. Formulas are greatly changed. Thousands of tons of secondary nutrients and an unknown quantity of certain minor elements are no longer obtaining a "free ride" to the farmer's fields.

Space here does not permit a review of the literature on the role of calcium, sulfur, and certain minor elements in crop production. Most people, however, agree that under certain soil conditions their application in fertilizers may be very beneficial. Michigan farmers used 88,000 tons of P_2O_5 in 1955. If they had applied it all as 0-20-0 or if they had applied it all as 2-12-6 formulated from 0-20-0 as a source of phosphorus, they would have applied 102,300 tons of calcium. This would have been 60 per cent of that which they did actually apply as limestone. Furthermore, the calcium in fertilizers is more soluble than that in limestone, and the fertilizers are usually placed in more intimate contact with seeds and plant roots. To be sure, there was some calcium in Michigan's 1955 fertilizer, but the amount was relatively small compared to that which would have been carried by the older low-grade mixtures.

The element sulfur is worthy of a little thought. Michigan farmers applied over 36,000 tons of nitrogen in 1955. If it had been applied as

ammonium sulfate (24.2 per cent S) they would have applied 43,560 tons of sulfur. Actually, very little was applied as that carrier.

Again, 88,000 tons of P_2O_5 applied as superphosphate would have furnished 51,700 tons of sulfur. Can this total loss of over 95,000 potential tons of sulfur each year be disregarded? In some localities and in some soils it is not important. Under other conditions it may be very important. More research along these lines is desirable.

Where nutrient applications are *very* high, it *may* be better to use formulations which do not include large quantities of unneeded substances such as calcium, sulfates, and chlorides. Thus salt effects may be reduced and unwanted residues avoided. For instance, the drainage water from the marsh already mentioned was found by conductivity measurements to be high in soluble salts. Led into a river, such salts might be harmful.

The city of Adrian, Michigan, takes water from a small stream which has in its watershed an intensive agricultural area. It is believed that the soluble salts in the water come from crop fertilizers. The concentration has been higher than desirable.

Copper may remain in soil in an available form for several years. At the Michigan muck farm, 6 pounds of copper applied in 1953 and 1954 increased 1956 Sudan grass yields from 2.9 to 14.8 tons green hay per acre (Fig. 3).

Boron, on the other hand, becomes rather quickly fixed into an unavailable form, where it has been applied to an alkaline soil. As a result, borax must be applied every year for crops sensitive to a lack of boron. This may be fortunate because one need not worry about including in the rotation crops, such as beans and oats, easily injured by borax.

Manganese is quickly oxidized in neutral or alkaline soils. As a result, it is a good practice to apply needed manganese salts for each crop and not to depend on residual effects.

IV. Nutrients from Organic Residues

Fertilizers are necessary on many soils for the production of soil-building legumes. Under some systems of management, the fertilization of green manures may be one of the best ways of applying nutrients for a following crop (see Fig. 1).

The corn grown in cropping system 4 (Table I) has yielded, over the 16-year period, 26 more bushels per acre than has that grown in system 6. Alfalfa in the rotation caused the increase in yield. Some of the beneficial effect of the alfalfa may be credited to the mineral nutrients released during decomposition.

Even grasses may be affected by mineral fertilizers applied during

FIG. 3. The effect of 5 pounds of elemental copper per acre on growth of Sudan grass on organic soil, pH 4.7. The carriers were copper sulfate and copper oxide. Experiments show that residual effects from copper may last 10 years.

previous years. At the Michigan muck farm in 1956 a good stand of Reed Canary grass remained on plots which had been fertilized during 1950 to 1954 but not in 1955 or 1956. Adjoining plots, never fertilized, had been entirely taken over by bluegrass. The difference in vegetation would surely have some effect on following crops.

V. Soil Acidification

The acidifying effect of ammonia and ammonium fertilizers is widely recognized but is generally being disregarded. With the use of nitrogen increasing so rapidly, this seems a serious matter. Volk (1956) has recently shown by lysimeter experiments that it may be very seri-

ous. His lysimeters were filled to a depth of 50 inches with Lakeland fine sand. The lower 40 inches was mixed subsoil of pH 5.56, and the upper 10 inches was surface soil of pH 6.27. Bermuda, one of three grasses grown over a period of four years, was fertilized with 420 pounds of nitrogen per acre, applied in 30-pound increments as NH_4NO_3.

At the end of the experiment the pH of the surface 2 inches of soil had fallen to 5.08 and that of the 2- to 10-inch layer to 5.70. Apparently there had been a movement of bases downward, as was indicated by the fact that the pH of the 10- to 18-inch layer had risen from 5.56 to 5.65. Where the total quantity of nitrogen applied was twice as great during the four years, the pH of the surface 10 inches dropped still lower, to 4.91, and that of the next 8 inches rose higher, to 5.78.

Acid soils are low in bases. Any fertilizer which results in loss of bases from such soils is bringing about soil depletion. The seriousness of the depletion will depend upon the original base content of the soil and the quantities of bases applied as lime or in mineral fertilizers.

The data reported in Table I show that a period of 16 years of cropping Sims clay loam did not bring about a reduction in pH. It is realized of course that the total quantity of nitrogen applied was not large and that this soil is naturally well supplied with exchangeable calcium.

Anthony *et al.* (1940) found that on certain acid sandy soils of Mississippi neutral fertilizers resulted in greater cotton yields than did acid fertilizers. They did not obtain this result, however, on clay soils, probably because the latter were better supplied with bases.

Some persons regard lightly the acidic effect of fertilizers. Limestone is cheap and correction would not be costly. However, farmers are not purchasing the lime. Agricultural lime applications in Michigan dropped from the equivalent of 968,000 to 425,000 tons of limestone per year during a period when nitrogen use rose from 8624 to the 36,581 tons used in 1955. This latter quantity of nitrogen applied as NH_3 would neutralize 65,845 tons of limestone, a quantity equal to 15 per cent of the total agricultural lime used during that year. Some of the nitrogen was applied as ammonium sulfate, so the actual acidic effect was even greater.

On specific soils where large quantities of nitrogen are applied yearly, this acidic effect may be even more significant. For instance, continuous corn production may call for 200 pounds of nitrogen per acre per year. At the end of five years, a ton of 90 per cent limestone would be neutralized. That cannot go on indefinitely without reducing pH and adversely affecting crop yields.

VI. Summary

Fertilizer is being applied to farm soils in ever-increasing quantities. Changes in technology and competition for business have resulted in

greatly different formulations. It is time to take a look at the effect which these changes are causing.

Soil test results show that phosphorus and potassium levels are building up in soils where crops are being regularly fertilized. This is especially true of phosphorus on mineral soils and potassium on organic soils. The accumulation of phosphorus and potassium is seldom relative so that fertilizer grade changes become necessary to maintain nutrient balance. Extremely high potassium levels lead to losses by leaching and luxury feeding, intensify magnesium deficiency, and eliminate response to sodium.

Secondary nutrients added in fertilizer may be beneficial in some soils but may build up to toxic levels where rates of application continue high. Residual benefits from copper may last several years. Boron and manganese, on the other hand, become fixed in unavailable forms so they must be applied each year and are not likely to be toxic a year after application.

Fertilizer nutrients become a part of green manures and crop residues and are thus carried over to be used by crops which follow. Where the nutrients make the green manures possible, their residual effect may be considerable.

Nitrogen use is increasing so rapidly that the problem of acidic effect must be reconsidered. The bases neutralized by heavy applications of nitrogen fertilizers may be cheaply replaced with limestone, but at present farmers are not buying the limestone.

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THE CONCEPT OF BRAUNERDE (BROWN FOREST SOIL) IN EUROPE AND THE UNITED STATES

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I. Introduction

The term "Braunerde" was introduced in 1905 by Ramann in the second edition of his textbook *Bodenkunde*. Since then the term has been used in many countries. It has become more and more evident that the name has been applied to a number of soils, often very different both in genesis and properties.

At the time Ramann introduced the term Braunerde no system of standardized terms for describing profiles had been developed, and

an individual's knowledge of the morphology of soils was almost restricted to the soils he had seen. Chemical and mechanical analyses of soils were very few or were unavailable.

1. *Ramann's Concept of Braunerde*

Ramann's definition was based mainly on the geographical distribution and on the supposed genesis of the soil. He considered "Braunerde," together with "laterite" and "Roterde," as members of the group of soils characterized by rock alteration ("Boden der Gesteinszersetzung"), through chemical weathering and leaching. Ramann (1905) stated: "The Braunerde are the most widely distributed soils in central Europe. They are the product of a temperate climate and moderate leaching. The soluble salts, including sulfates and carbonates, are leached from the upper soil layer. On the other hand, iron, aluminum, and phosphates are either not washed out or are only slightly washed out. Due to the presence of iron-hydroxide, the soil is yellow to deep brown, or if the parent material is red, brownish to reddish brown. The content of humus varies considerably but is however still sufficient because of its dark color to impart to the soil a dirty, unclean tint.

"The color of Braunerde gets darker, even blackish when the humus content increases. If the soil is first treated with diluted hydrochloric acid to a slightly acid reaction, and then with ammonia, one gets the color of the mineral soil. The humus material is as a 'Moder' mixed with the soil or flocculated and equally distributed among the mineral particles.

"The temperate climatic conditions of the Braunerde give rise to a predominant influence of the parent material on the soil.

"As a consequence, in spite of the general Braunerde character, one finds different soils on various parent materials. For this reason these soils are often distinguished according to the parent material (e.g., basalt soil, granite soil, bunter sandstone, etc.).

"The most important constituent of the soil is the 'clay,' a more or less iron-bearing dominantly colloidal weathering product of silicates. The kind of soil varies from heavy clay to light sandy soil."

In his definition of the Braunerde, Ramann did not make clear whether the soils do or do not have a textural B horizon or horizon of clay accumulation. Some have assumed from his statement that the typical Braunerde has no illuvial horizon of silicate-clay minerals. But, when he describes the distribution of the Braunerde as in France, the east side of England, a great part of Germany, Austria, south Sweden (partly), and parts of central Russia, pointing out that the zone of distribution narrows to the east and is limited by the Ural, it becomes

quite evident that he included soils with and without textural B horizons.

The rather general statement of Ramann permitted greatly different soils to be labeled as Braunerde by different authors, and the name came quickly into general use.

At the first international Agrogeological Conference at Budapest in 1909 Ramann and Glinka made an excursion to Polymar in the vicinity of Budapest, and studied soil profiles developed from loess, both under forest and in arable land. According to Glinka (1911) these soils were called Braunerde by Ramann, and were characterized in the upper horizon by signs of podzolization. This weakly leached horizon. was resting on a red-brown layer, that through its color and physical characteristics, plasticity, and stickiness, contrasted distinctly with the loess below.

Ramann, in his later work (1918) on the *Evolution and Classification of Soils,* placed the Braunerde in the class of soils of the temperate and the warm temperate humid region. Their formation, he believed, is due to the climatic environment (moderate evaporation and medium temperature) but also requires a special kind of parent material. Similar soils are also formed in the tropics under decidedly humid conditions without seasonal variations. They are to some extent local soils (Ortböden) or intrazonal. The coloring agent is yellow or red iron hydroxide. They are the dominant soil forms of western and middle Europe, but they also occur far to the south, in Italy, for instance.

Ramann (1918) also introduced the term Podzolic Brown Earth (Podsolige Braunerde) for soils that do not have an accumulation horizon of silicate-clay minerals but do have a weak accumulation of sesquioxides. However, he did not make a clear statement on the presence or absence of a bleached A_2 horizon. It is likely that he had in mind a weak Brown Podzolic soil and not a Brown Earth with a very thin Podzol developed in its A horizon.

Ramann (1928) stressed that soil color was the unifying characteristic that tied soils together. Consequently, in addition to Braunerde, he recognized Gray Earths, Black Earths, and Red Earths. He says:

"The designation of the climatic soil forms has up to the present been based with very few exceptions on the colour of the soil, since this is an external character which is easily recognized. The voice of the people has already been active in this connection: expressions such as Red Earths, Terra-rossa, Podzol, Tschernosem, Black Land are derived from the colour of the soil. The application of colour distinctions is upheld not only by the conspicuity of colour as a characteristic feature, but also by the fact that investigators of all nationalities have

used it as a distinguishing character. The expression Bleached Earth, for instance, implies that we are dealing with a soil from which all the iron has been removed; Black Earth indicates a considerable humus content, Brown Earth that the iron content of the soil consists mostly of brown hydroxides of iron—the form characteristic of humid climates—Red Earth that red hydroxide of iron—the form typical of warm climates—is present. But at this point it must be recognized that similar colorations can and do occur with dissimilar types of soil.

"Bleached Earths arise from the action of acid humus which is deficient in electrolytes as well as from the action of humus sols formed by soda. The number of Red Earths will probably be considerable as soon as Tropical Soils are better investigated.

"It would be a pity to give up the designation of soils according to their colours, for that would involve the loss of a number of ideas associated in our minds with colour and affording valuable clues as to the origin and properties of particular soils.

"Nomenclature and definitions are aids to the understanding; they are attempts to express in simple forms the knowledge which has been acquired. Hence we find the position and state of advancement of sciences most clearly reflected in their terminology, and this also most clearly expresses the progress of a science. At the present time the naming of soils according to colour meets the requirements of soil science; it seems expedient to retain it provisionally and to leave a change of the nomenclature to the future. We shall therefore retain the present nomenclature, but apply it in such a way as to express general properties. The colour names of soils must be redefined to cause them to rest on a climatic basis so that they have more than a local significance."

2. *The Concept of Braunerde in Central and Eastern Europe*

In central and eastern Europe the term Braunerde was quickly used and many studies were published on the genesis and the distribution of these soils. The problem of nomenclature and classification has been discussed by many soil scientists. The authors have tried to make a reasonably complete review of the literature on this subject, but no doubt some valuable papers have escaped attention or could not be consulted because of the language problem.

Murgoci (1909) appears to have been the first to use Ramann's term in a published paper and also to have coined the term "Brown Forest soil" as a synonym for Brown Earth.

He pointed out that the Braunerde was widely distributed in Roumania. He especially emphasized that in the hill area bordering the streams, the forest had invaded the zone of the Chernozems. Under the

influence of the forest vegetation, the soils lost their original character and were transformed into Degraded Chernozems or even to Brown Forest soils. Murgoci further says "the 'Braunerde' of Ramann is a Brown or Red-Brown Forest soil, that is different from the Russian Podzol and from the German bleached sand (Bleichsand). This Braunerde is everywhere related to very old oak forest, while the Podzol in Moldavia is related to the beech forest."

The "Braunerde," he says, "has a humus content from 3 to 5 percent and the soluble salts, including carbonates, are leached from the upper soil to a depth of one meter or more. Angular blocky structure, which is not nuciform, is very apparent in the subsoil where the color is slightly redder due to the presence of concretions and of skins of iron oxide." He further pointed out that Dokuchaiev had earlier shown the existence in Bessarabia of soils which he called "Brown soils of the Oak forest." Therefore, he suggested the name "Brown Forest soil" (Brauner Waldboden) in order to avoid confusion with the soils of the dry steppe, for some of which the name Brown had already been used.

According to Murgoci, the Brown Forest soil is different from the soil of the Russian forest-degraded steppe, soil to which he applied the name of "Gray Forest soil" used earlier by Dokuchaiev.

Glinka (1911) pointed out that both the name and the definition of the Braunerde by Ramann were unsatisfactory. For one thing, the name "Brown soil" was confusing, since it had been used by Dokuchaiev in 1889 for soils from the dry areas (chestnut, brown, and gray desert soils). Furthermore, Glinka was not inclined to consider the Braunerde as a new great soil group (Bodentype); he claimed that a great many Braunerde were characterized by the same horizon sequence as the Podzols and therefore were to be considered as a variety of the Podzols, that is, having a B horizon of illuviation.

Glinka (1911) stressed that the upper horizons of the Braunerde show podzolization and are resting on a red-brown illuvial horizon. This illuvial horizon, according to Murgoci, is also characterized by angular structure. For these reasons, Glinka and many other authors, such as Afanassiev (1922), Vilensky (1927), Stebutt (1930), and Florow (1924), had the opinion that the Braunerde of Ramann was simply a Degraded Chernozem in forested areas (Waldsteppen) developed on calcareous parent material.

Glinka (1911) also pointed out that the upper horizons of the so-called Braunerde in the soils of Poltava described earlier by A. A. Georgiewsky (*Materialen zur Taxation des Bodens des Government Poltava*. I. Lieferung. Kreis Poltava, 1890) and in soils of several other areas, including Siberia, all show the influence of distinct podzolization and that the underlying B is an accumulation horizon. This accumula-

tion horizon is very similar to the B horizon of the Braunerde in the vicinity of Budapest, and has a finer texture than the A horizon. The main difference is that the Budapest soil generally has a slightly redder color, has a greater thickness, and does not always show tonguing of the A_2 into the B.

In the profile described by Glinka in the vicinity of Novo-Alexandrya this tonguing is a general and very striking feature. In one profile Glinka describes a destruction of the B horizon starting from the underlying horizon. A translation of this profile description follows:

1. A_1	0–30	cm.	Gray humus horizon of the leached podzol.
2. A_2	30–48	cm.	Whitish-gray, equally podzolized in all parts.
3. A_3	48–60	cm.	The podzolization invades the reddish-brown mass in spots.
4.	60–98	cm.	Reddish-brown, compact, and sticky horizon, which differs strikingly in consistency from the other horizons of the described profile. In this horizon one often finds small soft spots and rarely whitish spots and veins.
5.	98–128	cm.	Whitish spots and veins start to invade gradually the reddish-brown compact mass.
6.	128–164	cm.	Reddish-brown mass occurs only in very fine layers, and the whole complex of the horizon is a whitish fragmental mass, that has a pseudo stratification. This mass is formed by the same compounds (constituents) as the spots and veins of the next upper horizon.
7.	164–210	cm.	The apparent stratification disappears; the profile takes in all parts a more or less equal gray tint, but on the gray clay one sees dark spots or small spots with undefinable waving contours.
8.	210–214	cm.	Narrow, weak formed dark fibers (Streifen) with signs of humus precipitation.
9.			Apparently unchanged loess.

The reaction with hydrochloric acid starts at 214 cm. immediately below the dark fibers.

The mechanical analysis of this profile is as follows:

	Horizons						
	2	3	4	5	7	8	9
>0.25 mm.	0.75	—	—	—	—	—	—
0.25–0.05 mm.	27.25	24.50	27.50	28.00	16.25	15.50	20.50
0.05–0.01 mm.	50.00	55.00	45.25	56.50	62.40	60.75	63.25
<0.01 mm.	22.00	25.50	27.25	15.75	21.35	23.75	16.25

The fraction <0.01 mm. from the horizons 2 and 4 has been further analyzed.

From the 27.25% <0.01 mm. of horizon 4

7%—0.01–0.005 mm.
2.75%—0.005–0.001 mm.
17.50%—<0.001 mm.

From the 22% of horizon 2

13%—0.01–0.005 mm.
2.25%—0.005–0.001 mm.
6.75%—0.001 mm.

The chemical analysis of this profile is as follows:

	Horizons							
	2	3	4	6	7	8	9	
Hygroscopic water	0.66	2.50	2.53	1.25	1.34	1.36	1.80	
Ignition loss	0.82	1.86	1.66	1.11	1.25	2.94	2.64	
SiO_2	88.23	82.57	82.44	84.70	84.06	80.82	79.63	(CO_2 1.20)
Al_2O_3	7.37	10.90	8.69	7.31	11.00	7.18	6.73	
Fe_2O_3	0.97		4.03	2.11		2.41	3.01	
CaO	0.69	—	1.63	—	1.53	3.26	3.04	(CO_2 gebunder 1.54)
MgO	0.49	—	0.78	—	—	0.88	0.63	
K_2O	0.81	—	1.61	—	—	1.69	2.07	
Na_2O	0.58	—	0.81	—	—	1.03	1.40	

It seems clear that Glinka described a soil with textural B, with tonguing from the A to the B, and with a strongly developed fragipan.

Several other soils, described in the same area, were leached of carbonates to only 2 m. or less and did not show a fragipan.

The brown color of the illuvial horizon, according to Glinka, is due to the decalcification. Several laboratory experiments proved to him that iron does not accumulate in a calcareous loess. He believed that in the formation of the reddish-brown horizon the iron migrated with the soluble humus compounds and that after the fixation of the iron, the lime is leached to greater depths. The lime can be reprecipitated with humus or as $CaCO_3$.

In 1914 Glinka again drew attention to the podzolized character of the so-called Brown Earth of western Europe. He considered the Brown Earths and the Gray Forest soils or Forest loams (the latter being characterized by a B horizon with reddish-brown color) as podzolic soils which occur in regions with a climate which had been drier at an earlier time than at present. Glinka believed that the presence of calcium carbonate in the parent rock is necessary for the formation of both Gray Forest soils and Brown Earths (or Brown Forest soils). A deciduous forest vegetation is also necessary for the development of soils with reddish-brown horizons. With increases in the mean annual temperature, the length of the vegetative period, and the amount of precipitation, one finds more active decomposition of organic matter. Podzol development becomes fainter and the reddish-brown horizons more strongly expressed. Thus the west European Braunerde seems to be the last stage of acidic Podzol weathering and constitutes the

transition from the Podzols to the "Roterde" and "Terra Rossa." According to Glinka, this idea was already expressed by Bogoslovski in 1903.

Ballenegger (1920), in his study on the chemical composition of the soil types of Hungary, used the name (Brown) Forest soil for the kind of soil which he believed to be the Braunerde of Ramann. In these soils Ballenegger recognizes the presence of a well-developed accumulation B horizon. In this B horizon, owing to enrichment with clay, there is a decrease of SiO_2 relative to Al_2O_3 from the A to the B (1.40 to 1.16). Ballenegger further pointed out that this is also the case with what he calls "Gray Forest soil," other podzolic forest soils developed under oak. There are differences between the Brown and Gray Forest soils in quantity of leaching but these differences do not seem to be significant. The principal differences, according to Ballenegger, are in the C horizon. Indeed, the Brown Forest soil has a calcareous loess in the C horizon, whereas the Gray Forest soil and other podzolic forest soils have a C horizon of lime-free clay.

Ballenegger said that both the Brown and the Gray Forest soils are products of acid weathering. The silicates in the upper soil are decomposed under the influence of the carbonic acid coming from the moder formation of the forest litter. The bases, which are partly fixed on silicic acid or on carbonic acid, are leached. The hydrates of iron and aluminum move downwards as colloidal suspensions under the protecting influence of humic substances. When they reach the subsoil they are precipitated because the bases in the subsoil are not leached to the same degree as in the topsoil. Thus, the subsoil still contains enough bases for the flocculation of the iron- and aluminum hydroxide solutions. Evidence for this is the fact that the maximum of accumulation takes place at the limit of the parent material (B_2). With increased leaching, the parent material becomes gradually poorer and poorer in bases, and the depth of the zone where the precipitation takes place also increases. As a consequence, the accumulation horizon becomes thicker and thicker.

Novák (1924), describing the relation between climate and soil in Bohemia, considers the Brown Earth as a climatic soil type and coins the name "Centro-European Brown Earth." Gray Forest soils are considered transitional between Brown Earths and ash soils (Podzol). In the transitional area to the steppe he also recognized a Brown Earth that corresponds to the Degraded Chernozem of the forested steppe.

The characteristics and the classification of the soils developed from a Chernozem as a consequence of invasion by forest, were discussed by Florow (1924). However, he used the term Forest Steppe soil instead of Brown Earth. According to Florow, a Degraded Chernozem is characterized by a more or less pronounced loss of the crumb structure

typical of the Chernozem. The soil becomes a Forest Steppe soil with the appearance of a reddish-brown horizon. In the Forest Steppe soil two stages of development, each subdivided into two substages, are recognized. In the first stage the humus-rich surface is directly underlain or includes part of the reddish-brown horizon. In the second stage one finds a bleached (podzolic) layer between the surface and the reddish-brown horizon.

It seems likely that the first stage corresponds to what has been called a Reddish Prairie soil in the United States, and the second stage seems to correspond to the Gray-Brown Podzolic, or perhaps, in the case of a strongly bleached podzolic layer, to the Gray Wooded soil.

Several other authors (Afanassiev, 1922; Treitz, 1912; Vilensky, 1927; Smolik, 1928; and others) have shared the point of view that the Brown Earth of Ramann was simply a Chernozem, degraded under a forest vegetation.

According to Stebutt (1930) the characteristic feature of Braunerde is the high degree of silicate weathering, whereas the eluviation and illuviation of sesquioxides and silica gels are slight. For this reason the soil does not have a bleached color but shows a characteristic, often dirty brown color. The dynamic system of the Brown Earths is not very stable, but may easily turn in the direction of podzolization or to the formation of Red Earths. In fact, transitions to Podzols are often found in north Serbia, and transitions to Red soils in south Serbia.

De Sigmond (1938) made a distinction between Brown Earths and Brown Forest soils. To him the Brown Forest soil was a forest soil of the Podzolic type (temperate zones), in which "the eluviation horizon cannot be detected with the naked eye," e.g., there is no visible boundary between the A and B horizon. Podzolization is evidenced "only by a partial leaching down from the upper horizon of the sesquioxides and their accumulation in the B horizon." According to De Sigmond, since only chemical analysis (a study of the hydrochloric extract, the absorption complex, and the water extract) will enable us to decide whether there is an A and a B horizon, many so-called Brown Earths are probably confused with the Brown forest soils.

It is very likely that the Brown Forest soil of De Sigmond corresponds closely to the Brown Podzolic soils of the United States. It also seems probable that many of what are now called Gray-Brown Podzolic soils and Sol Brun Acide were included. This seems to be the case, at least, if we interpret correctly his statement that one of the ways in which Brown Forest soils are formed, is under beech forest (page 53) where "the leaf-fall covering the soil decays rapidly, for its loose and humid character is favorable to bacteria and earthworms, which together produce good mild humus." Nevertheless, De Sigmond pointed out that where the climatic conditions do not favor a rapid decomposi-

tion of the leaf fall, one may find in beech forests an accumulation of acid humus, or even of dry peat. To the best of our knowledge in the case of a mild humus under beech forest one finds normally a Sol Brun Acide, whereas with an accumulation of raw humus one is more likely to find a Brown Podzolic or even a Podzol.

According to De Sigmond, "Brown Earths are forest soils of temperate zones, in which the podzolic horizon (horizon leached of sesquioxides) is replaced by an accumulation horizon of brown ferric oxide hydrate," and which are products of weathering induced by carbonic acid. Contrasting to the Brown Forest soils, which De Sigmond considers to be Podzolic soils, the Brown Earths are considered as being "siallite" soils, poor in humus or free of humus. However, De Sigmond pointed out that in certain cases the surface horizon of Brown Earths is of a dirty color, owing to the humus content, but this does not contravene the principle which groups these soils among the soils undergoing carbonic acid weathering; for the humus remaining in the soil is only what is called the inactive reserve which, the moment it becomes active, completely decomposes into CO_2 and H_2O, so that weathering takes place in a solution rich in carbonic acid. Contrary to the Brown steppe soils, which "owe their brown color not so much to the Fe_2O_3 content as to the humus content," in the Brown Earth soils the color is due to the presence of iron hydroxide.

Further, De Sigmond did not agree with Glinka, who included the Brown Earths with the Degraded steppe soils; in his (De Sigmond's) system these Degraded steppe soils are placed in the main type of degraded calcium soils.

A characteristic feature of the dynamics of Brown Earths is that, according to De Sigmond, though the silicates decompose, the leaching of the bases prevents the formation of zeolites, while the free sesquioxides and the silica gel remain in the places of formation—the upper weathering layer—where they accumulate. Therefore, the soils have no eluvial horizon, while the sesquioxides are practically stationary.

Many other authors, such as Mikhailovskaia (1937), Neganov (1938), and Gulisashvili (1942), have discussed the distribution and the characteristics of the Brown Earths; for the most part we have been able only to consult summaries of the papers mentioned. In 1948, Liverovskij introduced the term "Bleached Brown Forest soil" for soils having a textural B horizon, and the term "Podzolized Brown Forest soil" for those soils that show an illuvial horizon of sesquioxides. He made a distinction between the Brown Forest soil and the Gray Forest soil, the last one occurring also in Spain. Wilensky (1950) uses the same classification. Musiërowicz (1954) subdivided the Brown Earths

according to the parent material. He stated that the Brown Earths differ from the Brown Forest soil of Stremme, and are characterized by the absence of an eluvial and an illuvial horizon. In spite of the absence of a bleached horizon, the soils may have a pH that is as low as that of the Podzols; therefore he thinks that one could call them "cryptopodzolic Brown Earths." He further says that many authors believe these derive from Podzols that have lost their bleached horizon by erosion. The new soil map of Hungary by Kreybig (1954) mentions rusty-colored Forest soils, Podzolized Brown Forest soils, and (typical) Brown Forest soils. Rosow (1954), in his discussion on the classification of the soils of the U.S.S.R. according to the work of Gerassimov, points out that a distinction is made between Podzolized soils (Podzols), Gray Forest soils, and Brown Forest soils. He further mentions cinnamon-colored soils, which are "curious brown soils of dry mountain areas," that resemble the Mediterranean Brown soils.

Cernesco (1956) in his study on the soils between the Danube, the Carpathians, and the Black Sea uses the term Brown Earth for two groups of soils. The first group comprises:

a). The reddish-brown soils (also called rusty brown).

b). The brown soils and yellow-brown soils (also called Sylvestric Brown soils—eutrophic) which are believed to correspond to Ramann's Braunerde; these soils can be typical or podzolized and include the secondary Podzol.

c). The reddish soils, found only on residual clays.

The second group comprises the Acid Brown soils, developed under coniferous forest; they may be typical or podzolized and have as final term the primary Podzol and the mountain (alpine) brown soils.

Chiritza (1956) discusses more in detail the soils of the Carpathians. He distinguishes an inferior and a superior podzolic subzone. The following soils are mentioned in the inferior substage:

a). Brown Forest soils developed under deciduous or mixed forest with rich understory vegetation. They are characterized by a mull and a deep A_1 (15 to 30 cm.), a gradual transition of the horizon, the formation of silicate clay minerals, moderate liberation of iron hydroxide, and weak migration of clay and ferrohumic compounds. One finds the following genetic succession: incipient brown soils, brown soil with weak profile differentiation, typical brown soil, weakly acid brown soil (base saturation 80 to 94 per cent), acid brown soil (base saturation 60 to 80 per cent).

b). Yellow-brown Forest soils (pale brown), moderately acid, developed under the same forest but with a poor understory vegetation. They are characterized by a mull-moder or moder, acid and easily podzolized. (Moder has come to mean a well-aerated surface organic

horizon consisting chiefly of coprogenic material and partially decomposed plant remains showing the original cellular structure.)

c). Podzolic brown soils and podzolic brown-yellow soils, developed under oak and beech forest with rich understory vegetation. They have a mull-moder or moder humus according to the intensity of podzolization and an illuvial horizon of silicate clay and can develop into Podzols.

d). Yellow Podzols and ash-gray Podzols developed under oak and beech forest with acid-loving grasses in the understory. There is no raw humus accumulation, but one finds a well-developed illuvial horizon of clay and sesquioxides. Texture difference between A and B are prominent. The saturation is between 70 and 10 to 20 per cent.

In the superior podzolic subzone, the following soils are mentioned:

a). Acid brown soils and acid brown-yellow soils developed under Picea or beech forest with acid-loving grasses. They are characterized by a thin A_1, resting abruptly on an iron oxide B horizon; the pH is about 5 and the base saturation from 30 to 60 per cent.

b). Podzolic acid brown and yellow-brown soils, developed under Picea. The A horizon is also very thin (5 to 6 cm.), contains bleached sand grains, and rests abruptly on an iron oxide illuvial horizon. The pH is below 5 and the base saturation below 30 per cent.

c). Acid Podzols of the high region, with a distinct A_2 horizon.

It is very likely that the various soils described here are comparable to the soil sequence studied by Cline (1949) in New York, which included the Brown Forest, the Gray-Brown Podzolic, and the Sol Brun Acide, the Brown Podzolic and their transitions to Podzols; some Gray Wooded soils may also be included.

From this review of the literature in central and eastern Europe, it seems evident that the term Braunerde and names derived from this term have been used for many different soils. They seem to have the following in common: Most, if not all, have had a forest vegetation and show a brown color, at least in some horizon. Aside from these common features they may differ greatly. They may have a raw humus accumulation, a mull, or a moder. They may have a thick dark-colored A_1 or a very thin A_1. They may have no eluvial horizon or they may have an A_2 or even a bleached A. The absence of an illuvial horizon is often required; in other cases the presence of an accumulation horizon of silicate-clay minerals is considered characteristic; in still other cases the presence of an illuvial horizon of iron oxides is admitted. Many authors require a gradational character of the horizons but in quite a few cases an abrupt transition is described. For some soil scientists Braunerde is but a Degraded Chernozem, for others it is a climatic (Centro-European) soil.

One certainly is inclined to agree with Musiërowicz (1954) when he states that the "concept of Braunerde is yet not clearly developed."

3. The Concept of Braunerde in the Scandinavian Countries

Frosterus (1924), reporting on the activities of a Commission established in Stockholm for the nomenclature of the soils of the north European moraine area, gives the following definition for the Brown Earth in the Scandinavian countries: "Dirty brown color, due to the mixing of iron oxide and humus; lime and potash are leached, while the sesquioxides remain or are precipitated on the surface."

Lundblad (1924, 1934) did not share the idea expressed by Glinka that the presence of calcium carbonate in the parent material is necessary for the formation of Brown Earths. He made a comparison between the Braunerde and the Podzol in the Swedish forests and the gradual transition between the two types. Under the best beech forests one finds a typical Brown Earth profile, and under oak and mixed oak forest one also finds Brown Earth, although with a slightly different morphology. On the other hand, the forest Podzol seems to be characteristic of the coniferous forest (needle-leaf forests, rich in moss). The morphological and chemical differences between "Brown Earth" and "Podzol" are, according to Lundblad, the presence or absence of a leached horizon (Auslaugungsschicht) or bleicherde. This horizon is present in the Podzol but is absent in the Brown Earths.

Probably the mull horizon of the Brown Earth corresponds to the bleached horizon of a Podzol, and the litter horizon of a Brown Earth would be the equivalent of both the litter and the raw humus layer of a Podzol. The lower boundary of the mull horizon (A_1) of the Brown Earth is very gradual, especially under a beech forest where there is a rich earthy mull. Both the mull horizon and the brown earth underneath the mull have a relatively high content of "gel," almost equal in the two different layers, but in general this content is less than in the accumulation layer of a Podzol. This seems quite natural because no movement took place from a leached horizon to the brown earth. Mull and brown earth differ from each other chemically only in the different content of organic matter. The humus content varies greatly between different profiles but is highest in the mull. In the best beech forest mull, the organic matter content rarely reaches 10 per cent. In comparison to this, he mentions that the mull horizon of coniferous forest with a rich forest floor may have a humus content of 50 per cent.

Lundblad further pointed out that in many cases poor management of the beech forest was the cause of the degeneration that induced the formation of raw humus and a "Bleicherde" (Podzol bleached layer).

In other cases, the soil degeneration was due to natural invasion or to a planting of coniferous trees. According to Lundblad, it is possible to distinguish a Brown Earth from a Degraded Brown Earth and from a zon, reaches a maximum in the B horizon, and decreases rapidly in the Brown Earth the total content of gel shows a rather gradual decrease with depth; in the Podzol the content is very low in the bleached horizon, reaches a maximum in the B horizon, and decreases rapidly in the C horizon. In the Degraded Brown Earth the maximum is less pronounced. Very often a horizon of maximum content is present and can be found by analysis, but one cannot recognize it with the eye. Total analysis normally does not permit a distinction between Brown Earth and Podzol.

Also Tamm (1923), who demonstrated the occurrence of Brown Earth before some soil scientists, pointed out that this Brown Earth changes very quickly if beech forest is replaced by needle-leaf forest. He assumes that the formation of Brown Earth originates from the large quantities of fallen beech leaves. In a later study, the same author (1932) states that the Brown Forest soils are the climatic soil types in southern Sweden. Their natural vegetation is beech or oak forest. Lime-rich is well as lime-poor parent material can have typical brown soils. If the deciduous trees are displaced by conifers or heath, one finds Podzols or brown soils that develop into Podzols. In middle and northern Sweden, where the Podzols are the climatic soil, Brown Forest soils occur only on lime-rich parent materials or where the local climate is especially favorable.

We may assume that the Brown Earths on lime-poor parent materials at least as described by Lundblad and Tamm correspond to what are presently known as Brown Podzolic soils.

Aarnio (1925) is inclined to believe, after the studies of Lundblad and Tamm, that the cause of the soil formation of Brown Earth is trees which yield an abundant fall of leaves. The only tree of such kind which occurs in Finland is the hazel (*Corylus avellana*). An instance where hazels are grown over an area of some hectares in size is the Parish of Laitila in southwest Finland. The parent material is a moraine (till), which has originated from Rapakivi granite, and a description of the profile follows:

0–7 cm.	Humus-rich dark-colored layer of granular structure, loose.
7–17 cm.	Dirty brown layer (B_1 layer).
17–40 cm.	Gray-brown, containing humus (B_2 layer).
40+ cm.	Moraine (C layer).

The humus content drops from 10.51 per cent in the surface to 5.49, 2.60, and 0.47 per cent in the succeeding horizons. The sesqui-

oxides did not increase in the B layer, Al_2O_3 was about the same, and Fe_2O_3 was lower in the B_2 than in the B_1 horizon. Potash, phosphoric acid, and especially lime were highest in the A layer, which contains the most humus. The high humus content in the B layer causes the brown-gray color. Further, Aarnio points out that the formation of Brown Earth in this case was due to the vegetation. Through the abundant leaf fall the lime content has been concentrated in the upper layer and has flocculated the humus, changing it into a very slightly soluble type.

It is clear that Aarnio has described here as Brown Earth a soil that presently would be called a humus-rich Brown Podzolic soil.

Bjorlykke (1927) mentions the occurrence of Braunerde profiles in Norway, both in the region with weak or moderately humid climate and in the region with strongly humid climate. He states further that the pH of the soil in this last region seems to be between 4 and 5; the upper soil horizons are strongly leached but one rarely finds a bleicherde and a clear enrichment horizon is absent. All the profiles show the same horizon sequence: a humus layer, mostly directly followed by a brownish horizon, which in the depth fades to a grayer color. For the brownish horizon Bjorlykke uses the term Rusty Earth (Rosterde).

More recently Läg (1956) has described the distribution and the characteristics of the Brown Earths of Norway and their relation to Podzols.

One may conclude that probably most if not all of the soils that have been described as Brown Earths in the Scandinavian countries correspond to what is called now Brown Podzolic soil in the United States.

4. *The Concept of Braunerde in the British Isles*

In the United Kingdom Brown Earth or Brown Forest soil was generally considered as a soil without definite eluvial or illuvial horizons. Russell (1932) states that Chernozem and Brown Forest soils "are characteristically associated with definite climates." He emphasizes the nearly neutral reaction, the high amount of exchangeable calcium, and the neutral humus. "The Brown Earth profile consists of an upper layer containing neutral or almost neutral humus, the pH may be as low as 5, but is usually 6 to 7; below this comes a layer of brownish-coloured soil 50 cm. or so deep, cracking horizontally and vertically when dry and having a good crumbly structure."

According to Robinson (1949), Brown Earths or Brown Forest soils appear to correspond to the Gray-Brown Podzolic soils of the United States. He places the Brown Earths in the soils of the podzolic group. Their affinity with the Podzols consists in the complete leaching of

carbonates from the mature soil profile. They differ from the Podzol chiefly in their better base status and in their structure. The essential characteristics of the Brown Earth, according to Robinson, are:

1. The profile is completely leached of carbonate. Carbonates may be present in the C horizon or in the top soil as residues from added dressings. Drainage is free.

2. The colloidal complex is not highly base-unsaturated and the reaction is only moderately acid.

3. The humus is of a "mild" type, well distributed throughout the upper horizons without any tendency towards the development of a raw humus layer.

4. The composition of the clay complex in soils of primary weathering tends towards a SiO_2/R_2O_3 ratio of 2.0, representing a stage in desilicification intermediate between that of the Chernozem group and that of the ferrallitic soils of the tropics.

5. Free sesquioxides are present and give a brownish or reddish-brown color, which may be masked by humus.

6. There is no differential eluviation of silica or sesquioxides and the SiO_2/R_2O_3 ratio of the clay remains constant through the profile.

7. The soil structure is moderately granular.

8. The natural vegetation is deciduous woodland or scrub.

Robinson also gives some analytical data, which show that at least some Brown Earths may be very acid and have a pH of less than 5.

Clarke (1933) describes the Brown Forest soil as a type morphologically characterized by three definite horizons. The A horizon contains humus intimately mingled with the mineral material and has a distinct dark-brown color, a granular structure with tendency to increase in size to small nutty, and a loose porous consistence. The occurrence of free calcium carbonate is rare. The B horizon is considered to be an accumulation horizon, especially of silicate-clay washed in from above. The structure is usually small prismatic with a tendency for the structural elements to increase in size with depth; the consistence is compact and the color is a uniform brown. Calcium carbonate may sometimes be detected towards the bottom of this horizon. The C horizon consists of weathered parent material. According to Clarke the Brown Forest soils are very widespread and are formed primarily under broad-leaved forest. He suggests in 1937 a distinction between Brown Forest soils and Brown Earths. The Brown Forest soils could be defined as under forest, and the Brown Earths as under cultivation with an A horizon which has been changed.

Jacks (1934) states that the name of Brown Earth is rather comprehensive, and that only certain varieties of brown-colored soils belong to the type. Brown Earth is mainly associated with deciduous

forest, and the most typical variety is therefore accurately described as Brown Forest soil. There are no visible boundaries between the horizons. The color changes uniformly from the dark brown or black of the mull horizon to a light brown at the indefinite boundary between the soil proper and the parent rock. The mull layer is rather acid (pH 4.5 to 6.5) and shows sometimes a slight accumulation of iron and aluminum oxide.

R. L. Mitchel and A. Muir (1935) compare

a). Brown soils that have pH values of 5 in the upper horizons and only minor changes in mechanical composition with depth and

b). Soils on lime-rich parent materials, that are neutral or alkaline with occasional specks of lime in all horizons but have no definite zone of lime accumulation and show a slight mechanical transportation of clays to the middle layer.

They state: "Consideration of the above soils raises the question of the definition of the Brown Earths. From a survey of the literature, the characteristic feature appears to be the lack of morphologically pronounced horizons and, chemically, the absence of any movement of sesquioxides in the profile. On this basis soils *a*) and *b*) may be classed as Brown Earths, but if neutrality is taken as a further criterion, then group *a*) falls out. On the other hand, a zone of lime accumulation has been put forward as a characteristic feature; the marked increase in exchangeable Ca found in the middle and lower layers of the group *a*) soils is probably the nearest approach to this that can be expected on noncalcareous parent materials."

In the report of a discussion by the British Empire Section of the I.S.S.S. on "Brown Earths in Britain," in 1937, F. F. Kay states: "In Great Britain the Brown Earth group appears to include all those soils which are freely drained, contain no free $CaCO_3$, and in which the composition of the clay fraction is fairly constant throughout the profile. They may be only slightly leached and may have a high base status and neutral reaction; they may be more strongly leached and have an acid reaction, and they may even have a very high degree of base unsaturation.

"The essential difference between a Brown Earth and a podzolized soil would appear to be the composition of the clay fraction. This is usually constant throughout the Brown Earth profile, whereas in a podzolized soil a relatively siliceous A horizon overlies a B horizon enriched in sesquioxides from above.

"The Brown Earth group may be appropriately divided in the first place according to the supply of bases in the substratum."

In the British Soil Survey the subdivision of the Brown Earths seems to have been based mainly on the base status, but expressed on

the total soil and not on the clay fraction, that is, total exchangeable bases rather than per cent saturation.

Gallagher and Walsh (1942) state that the term Brown Earth is frequently applied to quite a variety of brown soils. Some of the brown soils on Silurian formations correspond with Ramann's original description as deep brown soils of virtually uniform profile and have a value for the SiO_2/R_2O_3 ratio of the clay throughout the whole profile of the order of 2. They mention also that, although the color of the profile of a deep brown soil on limestone bears some general resemblance to a "Brown Earth," there is a consistent difference of tint between them, which, however, is not easily defined. In some Brown Earths, they also have found a considerable degree of sesquioxide eluviation, although there is a conspicuous absence of a clearly defined leached horizon. They use the term Podzolized Brown Earth for this soil, which they considered to correspond to the "concealed Podzol" of the Russian classification.

Hall and Robinson (1945) state that Brown Earths, although having a higher base status than the Podzols, are definitely base-unsaturated and that their reaction is on the acid side of neutrality. There is no eluviation of sesquioxides and the composition of the clay complex remains approximately constant. All transitions to Podzols may be observed, but there is a group that might be given separate recognition, namely, the Gray-Brown Podzolic soils. They are soils of lower base status than the Brown Earths, showing some podzolization owing to slight translocation of sesquioxides. They grade into the Podzol, on the one hand, and into the Brown Earth, on the other. Most of the freely drained soils of Wales and Scotland might be assigned to this group. Recently, Mitchell and Jarvis (1956), in their description of the soils of the country round Kilmarnock, and also Muir (1956) state that the Brown Forest soils of low base status correspond to the Gray-Brown Podzolic soils of the United States.

In the system of classification of British soils, Avery (1956) groups Brown Earths and related soils in the major soil group of the "leached mull soils," defined as neutral to moderately acid forest, grassland, and cultivated soils with mull or nondystrophic moder humus. This group is subdivided into:

a). AC or weak A(B) soils (Brown Ranker and Regosol).

b). Braunerde like A(B) soils (normal Brown Earth, sandy Brown Earth, and ferritic Brown Earth).

c). With "textural B" or fossil or relic (B) horizon.

It appears from this literature review that in the United Kingdom and in Ireland several kinds of soil have been called Brown Earths, and seem to correspond to the Brown Forest soils, the Gray-Brown

Podzolic, the Brown Podzolic, and the Sol Brun Acide of the United States.

5. *The Concept of Braunerde in Germany and Austria*

Since the introduction of the term by Ramann a great many papers dealing with Braunerde have been published. It is almost an impossible task to give a complete historical review. However, one can find in the publications of Stremme (1930a), Laatsch (1938), and Kubiena (1953) a discussion of the literature and many references. Therefore this review will be limited to a discussion of the various concepts of Brown Earth.

Stremme (1914, 1926, 1930a, 1930b, 1936, 1950) in several publications has discussed the distribution, the morphology, and the genesis of the Braunerde. Prior to 1930b, he uses both the term Braunerde and Brauner Waldboden (Brown Forest soil). In the General Soil Map of Europe (1927), prepared by a committee under the chairmanship of Stremme (1927), only the term Brown Forest soil was used, but "Braunerde" is the title of his monograph in the *Handbuch der Bodenlehre.* On the soil map of Germany (1936), he uses only the name Brown Forest soil and states: "In relation to the special term Braunerde introduced by Ramann, it has been shown repeatedly that brown soils have many different origins and are of great variability." In 1930c, he substituted another term for Ramann's "Grauerde," since a color name may be used for soils only if the vegetation is indicated at the same time. He also introduced (1930c) the term Bleached Rusty-colored Forest Soil.

Stremme seems to disagree with the viewpoint of Glinka and many other authors that Brown Earths correspond to the degraded Chernozems of the forested steppe. To him the degraded Chernozems are "secondary podzolized Gray Forest soils of the forested steppe." He states that in those soils the podzolization (bleaching under the humus horizon) is weak and often hardly visible, and in contrast to the primary weakly podzolized soils, they have a rusty-colored B horizon. In this B horizon the iron is not uniformly distributed, but occurs in spots beside chocolate brown humus spots. The humus spots are remnants of the Chernozem and differ in color from the humus of a primary Podzol. Stremme states that, owing to the brown color of its B horizon, the secondary podzolized Gray Forest soil has often been described as Brown Forest soil, not only by Glinka but also by many other authors (Treitz, Marbut, Lundblad) (page 135). One is slightly surprised to read further (page 182) "In summary there is the following to say about E. Ramann's Braunerde, the Brown Forest soil of many authors: Braunerde or Brown Forest soils correspond to various stages in the

degradation of steppe Black Earth and K. Glinka's secondary podzolization."

According to Stremme (1936), and this viewpoint is shared by many other soil scientists, including Taschenmacher (1937) and Sellke (1934) the characteristic feature of the Brown Forest soils is the presence of a brown B horizon, with typical polyhedral structure; the peds have a great many fine pores and are coated with a reddish-brown skin, while the interiors of the polyhedrons are paler. The color is due to iron oxide and occasionally also to humus. Forest soils that have a brown B horizon without this typical structure and coatings are called "Rusty-colored Forest soils." Both the Brown Forest soil and the Rusty-colored Forest soil are subdivided into unbleached, moderately bleached, and strongly bleached, according to the presence or absence and the intensity of the bleaching. The B horizon of the Rusty-colored Forest soil is considered as an illuvial B horizon of the Podzol type. The origin of the B horizon of the Brown Forest soil, especially the unbleached variant, remains doubtful. Stremme seems to believe that at least the bleached variant has a real illuvial B horizon, but he does not exclude the possibility of its formation in place without illuviation. He seems to favor this interpretation for the unbleached variant. He points out that the unbleached variant seems to be confined to calcareous parent material and has a very limited distribution.

The subdivision of the forest soils by Stremme and his school might probably be correlated with the great soil groups in the United States as follows: Unbleached Brown Forest soil = Brown Forest soil; bleached Brown Forest soil = Gray-Brown Podzolic soil; unbleached Rusty-colored Forest soil = Brown Podzolic and possibly Sol Brun Acide.

Laatsch (1937, 1938) defines the Brown Forest soils as being characterized by advanced formation of silicate clay without destruction or migration of the clay. The brown color is due to iron oxide formed during clay formation. The horizon sequence is as follows: A = humic topsoil in mull form; (B) = lehmified subsoil, colored by iron oxide; C = unweathered. The transition between the horizons is diffuse. Further subdivision of the Brown Forest soils is based on the base status. Brown-colored soils that have an illuvial horizon are called Podzolic Brown Forest soils and are grouped with the podzolized soils in the category of soils undergoing destruction of the clay. Podzolic Brown Forest soils are characterized by the leaching of iron through the influence of humic and fulvic acid from the upper horizon and its accumulation in the B horizon. Laatsch seemed to disregard soils that have only a textural B without an accumulation of iron oxide, or at least these soils were grouped with the podzolized soils. In his more recent

work (1954), he used the terminology proposed by Kubiena and Mückenhausen.

Kubiena (1948, 1953) reintroduced the name Braunerde, which had been at that time almost abandoned for Brown Forest soil (Brauner Waldboden). He considered Braunerde as "neutral to moderately acid A(B) C soils of temperate climates with predominantly immobile, flocculated colloidal substances; the brown to light ochre colored B horizons are not enriched horizons but have been formed by deep reaching chemical weathering with good aeration and abundant but not excessive moisture (i.e., they are (B) horizons)." Between Braunerde and other soil types there exist various transitions. Strong acidification and coarse moder formation as well as the beginning of humic acid eluviation lead to podzolic Braunerde; partial peptization and mobilization of the ferric hydroxides and the colloidal substances in general in the presence of free silicic acid leads to *Braunlehm.*

The podzolic Braunerde is considered as a Semi-podzol, belongs to the Podzol class, and is described as a "soil with similar external appearance to *braunerde,* frequently derived from *braunerde,* with moderate humus sol movement and, in contrast to the *podzol,* moderate acid humus eluviation."

The Eupodzolic Braunerde has bleached sand flecks or a seam of bleached sand at the lower edge of the humus horizon; the Cryptopodzolic Braunerde lacks this characteristic but may be recognized by the humus form (predominantly acid moder), by the usually distinct difference in texture between the surface soil layer and the substratum, for there is a considerable increase in the content of colloidal substances with depth, and by the predominance of bleached grains in the humus layer.

According to Kubiena, there is a fundamental difference between (Braun) lehm and (Braun) erde. The designation *-lehm* (always used in combination) does not refer to a particular texture or structure but, like the designation *-erde,* refers to a distinct "total character" of micromorphology. The -lehm is a brown-yellow or red-colored soil formation of the tropics and subtropics, usually with "highly plastic, extraordinarily easily puddled clay substance, peptized by colloidal silicic acid, which in Europe occurs chiefly in the form of relict soils, but as such, is very widespread." The -lehms are further characterized by the "high mobility of the ground substance and the formation of numerous double-refracting streaks and fluidal structures by alignment of the particles." The "distinction between the Braunlehm relict soils and the externally similar Central European Brown Earth is particularly important."

The Braunerde have intensive chemical weathering, with good clay formation, but no movement of colloidal substances; shrinkage and swelling can lead to the formation of "nut-shaped" or "polyhedrical" structure. Thus, in the viewpoint of Kubiena, a brown soil with an illuvial horizon of silicate-clay minerals cannot be called a Braunerde but is a Braunlehm. It has developed either under tropical or subtropical weathering condition or on a sediment which has undergone such weathering in a previous cycle, possibly before its deposition. In his book on the soils of Europe one finds no reference to the "Sol brun lessivé" or to the "Gray-Brown Podzolic soils."

Kubiena subdivided the Braunerde into Centro-European and Meridional. The Centro-European is further subdivided into Eutrophic, Oliogotrophic, Calc, and Ferritic Braunerde. This terminology has been accepted by many soil scientists.

However, several authors, especially of the school of Stremme, have criticized the view of Kubiena that the formation of an illuvial horizon of clay accumulation was impossible without tropical or subtropical weathering or without podzolization. Altemüller (1956) studied several thin sections of Braunerde on loess and concluded that there was distinct movement of the clay, and E. Mückenhausen (1955) in his outline of a scheme of soil classification for Germany proposed the name "Parabraunerde" for those Braunerde having a textural B but without differential translocation of sesquioxides. In Austria also these soils have been recognized in recent years. Fink (1954) uses the French name Lessivé. Recently Kubiena (1956) appears to recognize the Parabraunerde as well as the typical Braunerde.

6. The Concept of Braunerde in France and Adjacent Countries

The term Braunerde (Sol brun, Terra brune, Tierra parda) was first applied in France and adjacent countries to any kind of Brown soil without any further distinction.

Agafonoff (1928) described the Braunerde of Ramann (sols bruns) as a "podzolic subtype intermediate between the typical Podzol and the Yellow-Red Mediterranean soil." He pointed out that in the Mediterranean region the Braunerde has a very wide distribution, much greater than the Terra rossa. In the early editions of Demolon's book, the term Braunerde was used with a general meaning.

Erhart (1935) subdivided the soils of the temperate region into Podzolic soils, Chernozems, and Brown soils. The Brown soils (or Braunerde) are described as "the characteristic soils of the regions, which, from the climatic and ecological point of view, are placed between steppe and forest. Up to a certain point, these soils can be considered as transition types between Podzols and Chernozems." In this

zone the soils have "a tendency to become Brown soils because the organic substances which decompose generally give a brown humus."

A subdivision of the Braunerde was made by Aubert in 1938. He seems to have introduced the name "Sol brun lessivé" in 1936, but the first use in a printed publication was by Oudin (1937). In 1938, Aubert (in Demolon) gave several profile descriptions of "sols bruns lessivés" (leached Brown soils) developed on loess in the Paris region. In his classification scheme, Brown soils were grouped in three different genetic series: the series of the Rendzinas, the Sols bruns, and the Sols lessivés.

In the series of the Rendzinas there was a subseries of Brown calcareous soils (Sols bruns calcaires) which was subdivided into "Sols bruns calcaires str.s.," with only one soil horizon and "Sols bruns calcaires lessivés," with an accumulation horizon of clay.

In the series of the "Sols bruns" no subdivision was made; these soils have no eluviation, except for soluble elements. Consequently, there is no differentiation into horizons. Most of the described typical profiles have a high pH, but one profile developed on pre-cambrian shales of the "Massif armoricain" is rather acid.

In a later publication (1952) these soils were studied in more detail, but Aubert did not make any subdivision of the "Sols bruns."

In the series of the Sols lessivés, described as soils with a podzolic evolution, with an illuvial horizon of clay, and a pale but not ashy A_2, Aubert distinguished the following types: Sols bruns légèrement lessivés (weakly leached brown soils), Sols bruns lessivés (leached brown soils), Sols lessivés (leached soils), sols podzolisés (Podzolized soils), and Sols podzoliques (Podzolic soils). The differentiating characteristics of these soils were mainly the nature of the organic matter, the thickness and color of the A_2, and the ratio of the clay contents of the A and B (leaching index).

Aubert's classification has been generally used in France by Oudin (1937), Hénin (1938), Bordas and Gouvernet (1947), Duchaufour (1948), and others.

In Switzerland, Pallmann (1932) and Etter (1943) described the distribution and characteristics of the Braunerde, especially in relation to the vegetation. Their central concept is a neutral or slightly acid soil with no horizon differentiation, although some members may be very acid. But in 1943, Pallmann also recognized a brown soil with a horizon of clay accumulation and coined the name "Weakly Podzolic Brown Earth."

In Italy, the term Brown Earth was used with a rather general meaning and without subdivision by F. Mancini (1955, 1956). In Spain, the term Brown Earth (tierras pardas) was used by Del Villar

(1937) and Albareda (1940). The first author named the Brown Earths of central Spain "Brown Dry Forest soils."

More recently, Kubiena (1953) introduced the concept of the "Meridional Braunerde" for "light-colored, humus deficient, usually sandy *Braunerde*," having only slight chemical weathering. They show micro-morphological characteristics both of the *Braunerde* and the *Braunlehm* and occur in the drier regions of southern Europe. "Signs of chemical weathering extend deep into the parent material, but, in contrast to the Centro-European Braunerde, little clay formation, clay enrichment or liberation of free ferric hydroxide occurs. There is practically no movement of substances." The authors had the opportunity to study some soil profiles in Spain with Kubiena and were convinced that in many cases the meridional Braunerde corresponds to the A horizon of what is called a Noncalcic Brown soil in the United States, while the underlying B horizon was called a "Braunlehm" by Kubiena.

In Belgium the term Brown Earth was also used for a long time without subdivision. In the loess area the horizon of clay accumulation was generally referred to as "terre à briques" (brick earth). Later these soils were called Gray-Brown Podzolic or, after the classification of Aubert, "Sol brun lessivé" and "Sol lessivé" according to the degree of leaching. Tavernier (1951) introduced the term Brown podzolic (Sol brun podzolique) in Belgium for soils with a B horizon chiefly of free sesquioxides and humus. Further descriptions of these soils were given by Dudal (1953), Manil *et al.* (1953), and Pecrot and Avril (1955). It is to be noted that most of the authors used the translation "Sols bruns podzoliques." G. Manil used "Terres brunes podzoliques." A distinction between the neutral or alkaline Brown Forest soil without a textural B and the acid members also without an illuvial horizon of clay was made by the Soil Survey Staff. On the basis of research work, especially that of Pahaut, and after discussion of the problem with Aubert, Tavernier (1952) introduced the name "Sol brun acide," translated into "Acid Brown Forest soil." This name was chosen in order to avoid confusion with the Oligotropic Braunerde and the Brown Earth of low base status, for these last names were often applied to soils with horizons of clay accumulation. Several recent publications of Pahaut (1954), Manil *et al.* (1953), Deckers (1953), and Pecrot and Avril give further information on the "Sol brun acide."

At the Sixth International Congress of the I.S.S.S., Aubert and Duchaufour (1956) presented a new system of soil classification. In this scheme various kinds of Brown Earths were grouped in almost the same way as in the earlier classification of Aubert. The Brown Calcareous soil, with or without a B horizon of clay accumulation, is still in the group of calcimorphic soils with the Rendzinas. The previous group

of the "Sols bruns" was called "Mull soils with A(B)C or ABC profiles," and was subdivided into a subgroup of Sols bruns with A(B)C profiles, of which the "Sol brun acide" is a member, and a subgroup of the "Sols lessivés" again subdivided on the basis of a leaching index. It should also be noted that in the Podzol group (called Soils with ABC profile and raw humus), the Sol brun podzolique (Brown Podzolic soil) was included.

From this review of the literature on Braunerde it appears that the recent classification of these soils in France is rather similar to that being used in the United States. The main difference is probably the position of the calcareous Brown soils with an ABC profile and the absence of the Noncalcic Brown in Aubert's system. The differences, however, may be more apparent than real.

7. *The Concept of Braunerde in the United States*

Marbut (1927) introduced the term Brown Forest soils in the United States. He considered the class a subdivision of the Pedalfers, but did not define it. He did say "the Brown Forest soils are dominant in the mid-latitude belt of eastern United States from Maryland and New Jersey westward to the Prairies." He also included a map which showed Brown Forest soils occupying nearly all Virginia, the mountain areas as far south as Georgia, most of Tennessee outside of the limestone valleys and the loess area, as well as Connecticut, southern New York, southern Michigan, southern Wisconsin, and all the Ozark highlands in Missouri and Arkansas.

Baldwin (1927) at the same time proposed the name Gray-Brown Podzolic soils, and defined the group as follows:

"Where undisturbed, the surface has a covering of leaf litter from deciduous trees, 1 to 3 inches thick, underlain by a very thin layer of nearly black leaf mold. The upper mineral soil horizon (A) is dark grayish-brown in the upper portion where organic matter is relatively abundant, grayish-brown or grayish-yellow below; the texture is generally silty or sandy loam; structure is single grain or, in the upper portion, soft granular; there is a roughly horizontal or platy breakage; reaction is generally acid, acidity increasing downward; the thickness varies with the composition of the parent material, up to 18 inches in very sandy material, down to 6 inches in very heavy soils. The second major horizon (B) is brown or yellow-brown in color; the texture heavier or higher in clay content than 'A'; the structure is prominent, the mass breaking readily into angular lumps, ranging in diameter from ½ to 1 inch, increasing in size downward; reaction is generally acid; thickness ranging from 1 to 2 feet. The parent material (C) is

variable, but in the United States is dominantly glacial drift of varying composition. Features of the chemical composition are: (1) a gradually decreasing content of nitrogen downward; (2) the absence of free carbonates and of free bases from the solum horizons; (3) a relative concentration of silica in the 'A' horizon; (4) a relative concentration of iron and aluminum oxides in the 'B' horizon; (5) an enrichment of phosphorus in the 'A' horizon."

Baldwin cited the Miami silt loam of central Indiana as representative of the class.

Conrey (1933) discussed the genesis and morphology of the Brown Forest soils of the eastern United States, following Marbut's 1927 usage and ideas of distribution. He pointed out that these soils typically had a B horizon with finer texture than that of the A or C. He pointed out that the older soils of the group lay in the southern part of the area, and commonly had a B with redder color than that in the most recent parent materials.

Kellogg (1930) referred to the Miami and similar soils of Wisconsin as Gray-Brown Forest soils. Marbut (1931) and Kellogg (1936) then adopted the name Gray-Brown Podzolic, and Kellogg again cited Miami silt loam as representative of this group of soils.

The term Brown Forest soils was reintroduced by Baldwin *et al.* (1938) for a group of soils dominantly saturated by calcium, lacking eluvial and illuvial horizons, and developed in temperate humid regions under a forest vegetation. They stated: "Brown Forest soils are here recognized as calomorphic because of their high adsorbed calcium. They seem to correspond to Ramann's original Braunerde, and are distinguished from the associated Gray-Brown Podzolic soils by lack of evidence of podzolization. They are somewhat leached but have not developed eluvial and illuvial horizons to any appreciable extent. Incomplete evidence indicates that Brown Forest soils may extend well into the Tropics."

In the glossary of *Soils and Men* (1938 Yearbook of the U. S. Department of Agriculture) the following definition is given of Brown Forest soils: "An intrazonal group of soils with very dark brown surface horizons, relatively rich in humus (mull) grading through lighter colored soil into the parent material, and characterized by slightly acid reaction, little or no illuviation of iron and alumina, and a moderately high content of calcium in the soil colloids. Developed under the deciduous forest in temperate humid regions from parent materials relatively rich in bases."

Baldwin *et al.* (1938) also introduced two other great soil groups which are a part of the problem of Braunerde, the Brown Podzolic and Noncalcic Brown soils. Thus, they recognized three great soil groups—

Gray-Brown Podzolic, Brown Podzolic, and Brown Forest, within the group originally called Brown Forest soils by Marbut (1927), and a fourth, the Noncalcic Brown, which is a part of our problem.

The definition of the Brown Podzolic soils given in the glossary of *Soils and Men* (1938) is as follows: "A zonal group of soils with a thin mat of partly decayed leaves over very thin dark grayish-brown humus-mineral soil and a trace of pale-gray leached A_2 horizon over a brown or yellowish-brown B horizon heavier in texture than the surface soil; developed under deciduous or mixed deciduous and coniferous forest in temperate or cool-temperate humid regions." This conflicts somewhat with the statement by Baldwin *et al.* (1938) in the same book describing the Brown Podzolic soils, as follows: "Leaf mat and acid humus over thin dark gray A, and thin yellowish-brown A_2 over brown B horizon which is only slightly heavier than surface soil. Solum seldom more than 24 inches thick." A third statement, conflicting to some extent with both of these, appears in a paper by Thorp and Baldwin (1938) that same year, where they state "The term Brown Podzolic soil has been applied to . . . soils . . . that have incipient development of Podzol but in which this development is so slight as to be very easily destroyed by slight erosion or shallow cultivation. Ordinarily the light gray A_2 horizon is not more than an inch in thickness . . . . It (the Brown Podzolic group) is very distinct in character from the Gray-Brown Podzolic soil which normally has a moderate or strong development of textural B horizon . . . ."

The Noncalcic Brown soils were defined in the glossary of *Soils and Men* as follows: "The zonal group of soils with slightly acid light-pinkish or light reddish-brown A horizons over light reddish-brown or dull-red B horizons developed under mixed grass and forest vegetation in a subhumid wet-dry climate." Thorp and Baldwin (1938) state that this name was chosen "to avoid confusion between these soils and the Braunerde of Ramann. The latter term has frequently been translated as Brown soil which would make for confusion since the two soils apparently are not the same."

No further great soil groups were proposed among the soils with brown B horizons until Bourbeau and Swanson (1954) suggested that the Wethersfield soils of Connecticut were more like the "European Brown Earths of low base status ('Sol Brun Acide')" than the Brown Podzolic soils or the Gray-Brown Podzolic soils.

Cline (1955) recognized the occurrence of Acid Brown Earths, with and without fragipans, in New York. His concept was that of the Sol Brun Acide, but the name was translated into English. He states "these soils have four principal horizons (A_1, A_2, B and C) like the Gray-Brown Podzolic soils, but the soil is more strongly leached, generally

more acid and lacks the distinct clay accumulation in the third horizon (B)."

"Acid Brown Earths with fragipans are like the Acid Brown Earths to a depth of 18 to 24 inches, but have a dense horizon slightly enriched in clay and slowly permeable to water below that depth."

Baur and Lyford (1956) give a further discussion of these soils, calling them Sol Brun Acide; this paper will be referred to later.

Krebs and Tedrow (1957) discuss the genesis of the Gray-Brown Podzolic soils and the Sol Brun Acide in New Jersey, but use the name Acid Brown Forest soils for the Sol Brun Acide.

Lyford (1956) reviewed the difficulties with the definition of the Brown Podzolic soils and Podzols. He pointed out that, in the classification of mapping units, the boundary between the two groups had fluctuated over the years, and that the boundary between the Brown Podzolic soils and the Sol Brun Acide was also likely to change in time as more knowledge about the soils became available.

II. Kinds and Distribution of Soils Called Braunerde and Brown Forest Soils

It is very apparent from the above review of the literature that, from the start, there has been confusion about the Braunerde and the Brown Forest soils. The ideas about both their genesis and their morphology have been at sharp variance.

It seems certain that much of the confusion follows from actual differences in the kind of soil studied by the various authors but called by the same name. Field examinations of soil profiles in various countries by the authors show that at least four distinctly different kinds of soil profiles have been called Braunerde or Brown Forest soils in the past. Most of these four kinds of profiles can be further subdivided into two or more currently recognized great soil groups. The differences in the kinds of soil are fundamental, and there is no occasion for surprise at the varying concepts held about the morphology and genesis of the Braunerde. The four major kinds of profiles, their general distribution in Europe and the United States, and the names used for them in recent years are discussed in the remaining part of this paper. A generalized map of western Europe and the United States is included, showing the larger areas of occurrence of the different kinds of soil which have been called Braunerde or Brown Forest soil.

This map is highly generalized and undoubtedly contains many inaccuracies. It is based on general knowledge for the most part in western Europe and the western part of the United States, as few detailed modern soil maps are available in those areas. The authors believe, however, that it presents a reasonably accurate picture, considering

the scale, of the areas where one can find the various kinds of soil which have been called Brown Forest soil, Braunerde, or both.

The classification of these soils follows that of Baldwin *et al.* (1938) as modified by Thorp and Smith (1949) with the following exceptions:

The Brown Forest soil (Braunerde) of Baldwin *et al.* is referred to here as "Base-rich soil with (B)" to avoid confusion.

Sol Brun Acide is considered an additional great soil group, and the definition of Baur and Lyford (1956) is followed.

The term Brunizem is used instead of Prairie soil, as proposed by Simonson *et al.* (1952). The definition follows that of Prairie soils given by Smith *et al.* (1950).

The term Rubrozem is used as defined by Bramao and Simonson (1956).

The terminology used in profile descriptions follows the *Soil Survey Manual* (1951).

1. Soils Having a (B)

The (B) (pronounced "B parenthesis") was defined by Laatsch (1938) as a horizon resulting from chemical weathering and oxidation of the iron without illuviation. He says "the symbol (B) is used to indicate that it is not, as in the podzolized soils, an horizon enriched with colloids that have been washed in in the form of sols, but an horizon of intensive weathering."

Soils of this broad class might be defined as having an A(B)C horizon sequence. They differ widely in their base status, ranging from calcareous to extremely acid. In the more acid members there may be a fragipan developed between the (B) and C. Subdivisions of this class have generally been made according to the base status.

a. The Sol Brun Acide. In the United States, these soils have at various times been included by some with the Brown Podzolic soils or the Gray-Brown Podzolic soils, but by others they have been included with the Lithosols and Regosols because of their weak horizon development. Their recognition as a distinct great soil group has been recent. Bourbeau and Swanson (1954) used the name Brown Earth of low base status. Cline (1955) used the name Acid Brown Earth for these soils; Baur and Lyford (1956) used the name Sol Brun Acide; and Krebs and Tedrow (1957) used the name Acid Brown Forest soil. Earlier uncertainty about the classification is illustrated by the use of the term "Brown Podzolic or Gray-Brown Podzolic?" by the Soil Survey Laboratory (1952), and "lithosolic soils with faint horizons," "skeletal soil," "shallow soils," and other terms in the mimeographed descriptions of individual soil series of the United States.

In Europe they have been called Sol Brun Acide by Aubert and

Tavernier (1952), oligotrophige braunerde by Kubiena (1953), Braune Waldboden geringer Sattigung by Laatsch (1937), Brown Earth of low base status by Kay (1937), and simply Braunerde or Braune Waldboden.

Perhaps the acid kind of profile represents the original Braunerde of Ramann, since it is common in the mountains of Bavaria where he worked, many of his soils were described as being in forest, and the forests are largely restricted in the mountains. A description of a profile from the forest of St. Hubert near La Roche in the Belgium Ardennes, representative of the more acid soils having a (B), is as follows:

Horizon	*Inches*	*Description*
A_0		Partly decomposed beech leaves with a mixture of well-decomposed leaves and coprogenic material.
A_1	0–3	Dark gray (10YR 3/1) when moist, gravelly loam; friable when moist and slightly sticky when wet; moderate fine crumb structure; smooth abrupt lower boundary.
A_3 or $(B)_1$	3–14	Dark yellowish-brown (10YR 4/4) when moist, gravelly loam with strong, fine crumb structure; friable when moist, slightly sticky when wet; smooth gradual lower boundary.
$(B)_2$	14–32	Yellowish-brown (10YR 5/5) when moist, gravelly loam, not discernibly heavier than overlying horizons; friable when moist, slightly sticky when wet; structure mixed, with some subangular blocky peds, but bulk of material massive, breaking to moderate medium crumbs, no discernible clay skins; abrupt lower boundary.
D	32+	Weathering siltstone.

The profile was described on a steep slope with about 30 per cent gradient facing northwest. The parent material was obviously unrelated to the underlying bedrock and is presumed to have been a solifluction deposit. There were very few evidences of earthworms in the soil.

A common variant of this type of profile occurs on gentler slopes and has a fragipan at about 20 to 30 inches. A description of a representative profile in the same forest of St. Hubert in Belgium is as follows:

"Sol Brun Acide" with fragipan

Location:	Saint-Hubert, Luxemburg, Belgium, near the "Fange de la Flache."
Elevation:	Approximately 525 m.
Relief:	Level plateau with about 1 per cent slope to the north; the "fange" (peat) starts at about 50 m. of the profile.
Vegetation:	Beech forest with Luzula ("Hêtraie à luzule fraîche"). The average height of the beeches is 25 to 30 m. The natural regeneration is very poor, probably partly because of the game (wild life).

Drainage:		Moderately well drained; very little surface runoff under the trees, moderate internal drainage to the compact subsoil (fragipan), then slow. Moderately rapid infiltration, moderately rapid permeability.
Parent material and age		Rather homogeneous, slightly reworked loess deposit of Würm (Wisconsin) age with few quartzite stones, resting at about 60 to 70 cm. on a solifluction deposit of gravelly silt loam, also of Würm age.
Biologic activity:		Mold and fungi under the trees; some ants but few earthworms.
Climate:		Mean annual temperature about 7° C., the average temperature of the growing season about 13° C. Length of the frost-free season is 150 days. Mean annual precipitation—1200 mm. Rains occur throughout the whole year with two slight maxima in July and December. Fogs are frequent, both in the spring and in the summer.
A_0 and A_{00}	1½–0″	Leaf litter of beech and oak in decomposition with lenticular discontinuous black (5YR 2/2) masses of entirely decomposed leaves and coprogenic material.
A_1	0–2″	Very dark brown (7.5YR 2/2) when moist, silt loam; mostly weak fine crumb structure, but in places nearly massive with tendency to platy structure; friable, slightly sticky; few small roots. Where structure is crumb there is a smooth clear lower boundary, but in places with very thin lenses of a bleached layer (podzol A_2) and a layer of a few mm. thickness of iron accumulation, the lower boundary is abrupt.
A_3	2–9″	Dark yellowish-brown (10YR 4/4) when moist, silt loam, few gravels; moderate fine platy structure, becoming weaker with depth; friable when moist, slightly sticky; many small roots, smooth gradual lower boundary.
$(B)_1$	9–15″	Yellowish-brown (10YR 5/5) silt loam, few gravels; moderate fine subangular blocky structure; friable, slightly sticky, medium to few rootlets; smooth diffuse lower boundary.
$(B)_{2g}$	15–30″	Light yellowish-brown (10YR 6/5) silt loam, few gravels in the upper part, but gradually increasing in number with depth; medium moderate subangular blocky structure, with a tendency to coarse platy structure in the lower 8 inchs of the horizon; few distinct fine mottles, becoming medium and common in the lower part of the horizon. Very few roots; the trace of an old root, with bleached center and reddish-brown fine border, crosses this horizon at an oblique angle; smooth distinct lower boundary.
Cm	30″+	Reddish-yellow (7.5YR 6/8) and light yellowish-brown (10 YR 6/4) gravelly silt loam, many coarse quartzite fragments; structureless massive or squamous structure, firm, no roots.

Data on this profile are given in Table I.

TABLE I

Analytical Data

Depth (inches)	Horizon	Very coarse sand 2–1	Coarse sand 1–0.5	Medium sand 0.5–0.20	Fine sand 0.20–0.10	Very fine sand 0.10–0.05	Silt 0.05–0.002	Clay <0.002	0–20
		Particle size distribution (in mm.) per cent							
0–2	A_1	5.6	3.8	2.3	3.8	2.7	63.4	18.4	50.6
2–9	A_3	5.4	3.2	2.4	3.0	3.6	60.2	22.2	56.6
9–15	$(B)_1$	3.8	2.7	2.7	3.9	2.6	59.2	25.1	58.4
15–30	$(B)_{2g}$	4.5	2.9	2.7	3.2	3.7	59.7	23.1	56.9
30+	C_m	6.8	3.6	2.0	1.7	3.3	58.0	24.6	60.1

pH KCl	pH H_2O	Humus	Total exchange capacity (meq./100 g.)	Inorganic exchange capacity (meq./100 g.)	Organic exchange capacity (meq./100 g.)	Fe_2O_3 HCl	Fe_2O_3 free
3.1	4.0	7.98	—	8.05	—	—	—
4.2	4.5	1.80	8.48	6.56	1.22	3.0	2.8
4.3	4.6	0.64	6.56	—	—	3.3	2.9
3.6	4.1	0.46	6.45	—	—	3.4	2.9
4.0	4.4	0.09	9.88	—	—	4.2	3.3

This profile was examined during the excursions after the first meeting in Ghent in 1954 of the Subgroup for Soil Classification and Survey in Europe of F.A.O. The general characteristics of the acid Brown Earth or acid Brown Forest soil were summarized by Tavernier *et al.* in the Guide to the excursions as follows:

1. Thin or no A_0 horizon.

2. Thick A_1 horizon (± 10 cm.) with a crumb structure in the well-developed profile.

3. The A_3 horizon has a crumb or platy structure or even a polyhedral structure in the most clayey profiles.

4. The (B) horizon has a polyhedral structure, the texture of this horizon is very similar to the texture of the preceding horizons, clay coatings are absent, the color is slightly more reddish than that of the upper and lower horizon.

Additional data on selected profiles of Sol Brun Acide are given in Table II, to compare the Sol Brun Acide with the Brown Podzolic soils, the group with which they have most commonly been confused in the United States.

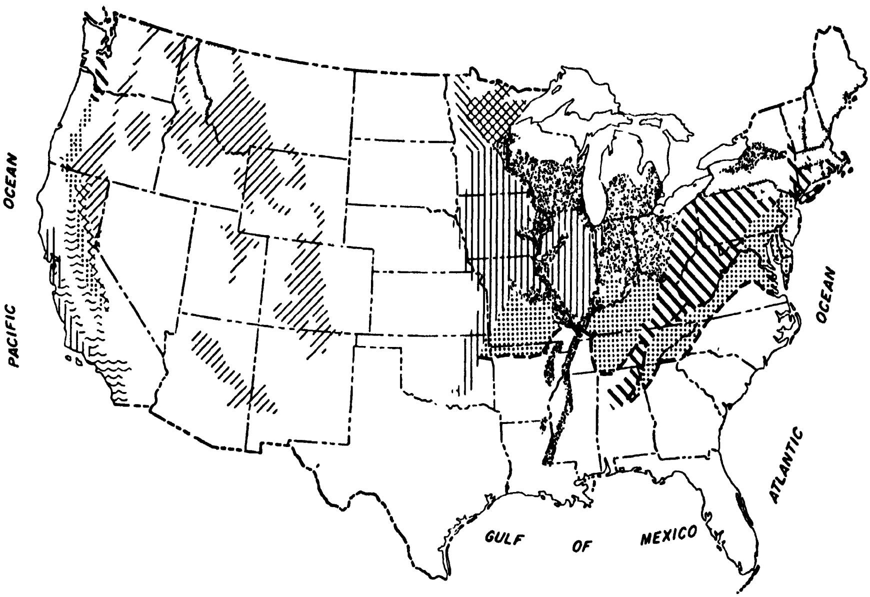
The authors have observed that profiles of the above kinds are restricted largely to soils forming from acid, but not extremely acid, parent materials, in the more humid parts of Europe and the United States.

In western Europe they occur chiefly in the highlands—the Ardennes in Belgium and France; the Eifel, Black Forest, Harts, Thuringen, and Bavarian mountains; the Vosges, Massif Central, and Massif Armoricain in France; and in the mountains of Austria, Italy, and Yugoslavia.

In the United States they are common in southern New England, New York, the Appalachian plateau extending south to the highlands of Tennessee and west to include some of the soils from the acid drifts of Ohio and Minnesota. They are found again on the West Coast in Washington and Oregon. Examples of series would include Muskingum, Rayne, Weathersfield, and Powell, as currently defined. The major areas where these soils occur commonly are shown on Figure 1 on pages 250 and 251. It should be noted that other kinds of soils occur in these areas, and that the Sol Brun Acide can also be found outside of these areas.

b. Base-Rich Soils Having a (B). At another extreme of the class of soils having a (B) are those forming in base-rich or even calcareous parent materials. A profile typical of this class was described on the University of Leeds farm near Leeds, England. The soil was forming in a calcareous drift of Wisconsin age. The forest had been clear cut and replanted a year or so before the description was written. The profile was as follows:

Horizon	*Inches*	*Description*
A_1	0–3	Very dark brown (10YR 2.5/2) when moist, weakly calcareous heavy loam or light clay loam; very friable when moist, slightly plastic when wet; moderate fine and medium granular structure, granules being largely earthworm casts; lower boundary is clear and smooth, but the transition to the underlying horizon shows much mixing by worms, with reddish-brown worm casts appearing in the lower part of this horizon, and very dark-brown worm casts continuing into the underlying horizon. pH 6.7.
(B)	3–14	Reddish-brown (5YR 4/4) moist calcareous heavy loam or light clay loam, friable when moist, slightly plastic when wet, structure of weak subangular blocky peds, mixed with moderate medium granules (worm casts); scattered limestone pebbles throughout horizon; very porous, with many worm holes. pH 7.8.
C_1	14–20	A mixture of material similar to horizon above with a high proportion of soft magnesium limestone.



1. SOILS WITH a (B)

Sol Brun Acide mixed with Podzols and Brown Podzolic soils on highly quartzic parent materials, Red-Yellow Podzolic soils on acid fine and moderately fine parent materials, and Gray-Brown Podzolic soils on calcareous or basic fine or moderately fine parent materials.

Base-rich soils having a (B) in common scattered areas mixed with Gray-Brown Podzolic soils on moderately calcareous parent materials and Sol Brun Acide, Brown Podzolic soils and Podzols on acid parent materials.

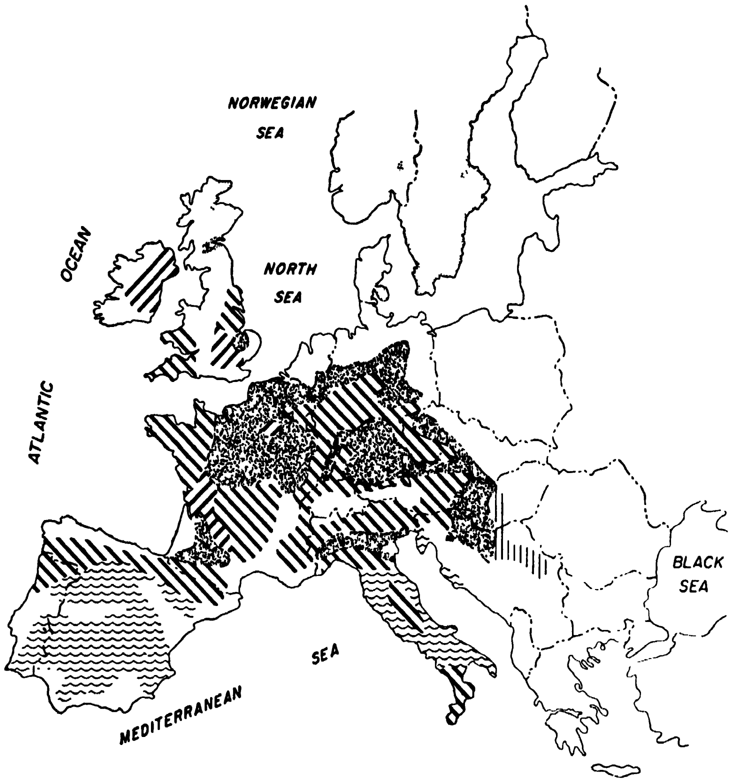
3. DARK COLORED SOILS BORDERING THE STEPPES

Degraded Chernozems, widely scattered and mostly in small areas.

Degraded Brunizems and Degraded Reddish Prairie soils, both widely scattered in small areas interspersed in larger areas of Brunizems and Reddish Prairie soils.

Degraded Chestnut soils in scattered areas, interspersed with Chestnut, Brown, and alpine soils.

FIG. 1 (left).



2. BROWN PODZOLIC SOILS

Brown Podzolic soils principally, on well and moderately well drained sites, with scattered soils having a (B) on highly calcareous parent materials in Scandanavia.

4. GRAY-BROWN PODZOLIC SOILS AND RELATED GROUPS HAVING AN ILLUVIAL B OF CLAY ACCUMULATION

Gray-Brown Podzolic soils principally on well and moderately well drained sites.

Red-Yellow Podzolic soils principally on well and Moderately well drained sites.

Gray wooded soils on calcareous and basic parent materials mixed with some Podzols on sands and Sol Brun Acide on acid medium textured parent materials.

Noncalcic Brown soils, interspersed with Terra Rosa soils on hard limestones, Regosols and some Grumusols and other intrazonal soils.

Marbut's (1936) boundary between Gray-Brown Podzolic and Red-Yellow Podzolic soils.

FIG. 1 (right).

In the United States soils of this character have chiefly been called Brown Forest soils, following the definition of Baldwin *et al.* (1938).

This concept has also been adopted in Canada, as Stobbe (1952) has described similar soils as Brown Forest soils.

Soils of this character have been called "Sol brun" and "Sol brun calcaire" in France by Aubert *et al.;* Red and Brown calcareous soils in England and also Brown Earths of high base status; "Nicht gebleichter (or kaum) Braune Waldboden" by Stremme (1930c), or "Brauner Waldboden hoher Basen Sattigung" by Laatsch, Eutrophic Braunerde by Kubiena (1953) and Mückenhausen (1955) in Germany.

In Europe, they occur on calcareous or base-rich parent materials, throughout Great Britain, southern Scandinavia, Germany, Switzerland, Austria, Belgium, and France. A great many of these soils are cultivated, but they occur also under rich forest, mostly Querceto-carpinetum.

In the United States these soils are known chiefly in the forested area in southern Wisconsin and Indiana, eastward to New England. The areas of these soils in the United States are very small, and they are largely surrounded by Gray-Brown Podzolic soils. Examples of series are Rodman, Kars, and Benson.

2. Brown Podzolic Soils

The definition of Brown Podzolic soils by Baldwin *et al.* (1938) does not distinguish clearly between the Brown Podzolic soils and the Sol Brun Acide discussed above. Thorp and Baldwin (1938), however, made a clear distinction when they said "The term Brown Podzolic has been applied to members of the Gloucester, Merrimac, Charlton, and a number of other soils of New England and New York that have incipient development of Podzol but in which this development is so slight as to be very easily destroyed by slight erosion or shallow cultivation. Ordinarily the light gray A_2 horizon is not more than an inch in thickness and in many places *the brownish organic B horizon characteristic of Podzols*[1] lies almost immediately below the duff." It is clear from this statement that the B horizon of Brown Podzolic soils was considered to be the same kind of B as that found in the Podzols of New England, one in which there has been an accumulation of sesquioxides and humus.

The presence of an illuvial B at or so near the surface might at first glance seem to be impossible. However Aarnio (1925) has pointed out that the iron might come from the forest litter, and an illuvial horizon might form at the surface. Thorp and Baldwin (1938) suggest that the A_2 is thin and can easily be destroyed by shallow cultivation. The authors have also seen convincing field evidence that the A_2 may be mixed

[1] Italics by authors.

with the B by earthworms. For example, the Ahmek soils in Minnesota normally have no A_2, but small areas in which the original A_0 formed under the pine forest has not been destroyed by fire usually have an A_2 1 to 2 inches thick. At the edges of these relict patches of A_0, the A_2 disappears gradually. First a few brown worm casts appear in the A_2; a foot or two away there may be only a few small remnants of A_2 not destroyed by worms, while in the vast bulk of the area there is no A_2 horizon. The dominant vegetation on these soils today is a broadleaf deciduous tree—the *Populus tremuloides.*

Mixing can also take place without the influence of man. Denny and Goodlett (1956) point out that the roots of falling trees bring the B horizon to the surface, and that often an A_2 may be found buried in the mounds. They conclude that in Potter County, Pennsylvania, most of the soils are disturbed every few hundred years by the roots of falling trees. Other possible means of mixing exist, but no studies have been found in the literature.

Stephens (1956) has pointed out that the uprooting of trees was a normal process before man began to cut the forest. He dated the tree falls for the past 500 years in a small area of the Harvard Forest with Brown Podzolic soils, and found 14 per cent of the area to have been disturbed in that time.

Studies of Podzols, Brown Podzolic, and Brown Forest soils were reported by the Soil Survey Laboratory (1952), including profile descriptions and laboratory data. Study of these data and additional unpublished data for the same profiles reveals no consistent difference in kind between the B horizons of the Podzols and the B horizons of the Brown Podzolic soils.

The B horizons of both Podzols and Brown Podzolic soils have consistently low or very low base saturation; organic matter contents are relatively high; C/N ratios of the Brown Podzolic B horizons are wide to very wide and in line with the literature reports on C/N ratios of the B horizons of Podzols; free iron oxide contents are approximately the same; clay contents are low. Summarized in Table II are some of the data for the B_2 horizons of Podzols, Brown Podzolic soils, and Sol Brun Acide, as reported by the Soil Survey Laboratory (1952). On the basis of the descriptions, the data, and some additional field observations, the authors have in some instances changed the classification of the series as published. This was necessary because of the inclusion of Sol Brun Acide profiles with the Brown Podzolic group, and the inclusion of Brown Podzolic profiles in the Brown Forest group. It should be remembered that the purpose of the study was to clarify the concepts of the great soil groups, and the classification published was made during the early stages of the study.

Nygard *et al.* (1952) have considered the Ahmeek soils to be Brown

TABLE II

Comparative Data on B_2 Horizons of Podzols, Brown Podzolic, and Sol Brun Acide Soils

Series	Thickness of B_2	Thickness of A or A_2	Base sat. of B_2	Free Fe_2O_3 in B_2	Ratio[1] Free Fe_2O_3 B_2/C	Ratio[1] Free Fe_2O_3 B_2/A	Organic carbon in B_2	C/N[1] in B	Clay in B_2 $<2\mu$
	inches	inches	%	%	%	%	%	%	%
					Podzols				
Klaus	3.0	1.5	5	1.4	5.7	3.1	2.7		4.1
Klaus	4.0	3.0	1				9.4		5.0
(Unnamed)	0.5	.5	5				5.1		4.0
Hiawatha	5.0	8.0	9				1.0		6.0
Hiawatha	9.0	7.0	8	1.5	4.7	3.8	0.8		5.9
Iron River	4.0	3 0	27				1.6		8.8
Iron River	4.0	4.0	20	2.0	2.1	2.0	1.9		8.6
Berkshire	3.0	1.5	5				4.1		9.1
Worthington	5.0	4.0	4	5.5	2.0	10.0	4.2		3.6
Lectonia	4.0	9.0	9				5.7		3.4
Whidbey	3.0	2.0	25				0.7		7.1
Whidbey	3.0	1.0	21	1.4	3.6	4.0	1.0		7.9
Average	4.0	3.7	12	2.3	3.6	4.6	3.2		6.1
					Brown Podzolic Soils				
Alderwood	1.0	0.5	15	1.6	2.3	0.8	2.7	18	5.1
Everett	2.5	0.5	8	1.4	1.6	1.4	1.8	26	7.9
Alderwood	6.5	0.5	8				1.8	17	3.2
Everett	6.0	0.25	17				1.3	13	6.9
(Unnamed)	2.5	0.5	15	1.6	1.3	3 5	1.7	16	19.5
(Unnamed)	4.0	1.0	26				1.5	14	19.4
Waits	1.5	0.25	12	1.2	1.8	4.5	1.8	17	9.5
Waits	1.5	0.25	14				1.9	17	8.7
Pend Oreille	3.0	0.25	28				1.4	13	4.5
Pend Oreille	1.0	0.25	10	2.1	2.9	3.7	4.3	32	5.8
Ahmeek	4.0	5.5	26	3.4	0.9	1.3	1.6		14.8
Ahmeek	4.5	2.5	11	2.4	1.8	1.6	2.8		9.9
Clymer	5.0	3.0	6				3.3	15	13.3
Paxton	12.0	4.0	4	3.0	2.7	1.5	1.2	20	8.5
Gloucester	8.0	4.0	14				0.5	16	6.2
Acton	9.0	4.0	2	1.6	2.7	1.0	1.6	17	5.6
Average	5.8	1.7	14	2.0	2.0	2.1	1.9	18	9.3
				Sol Brun Acide, or Acid Brown Earth					
Holyoke (Mass.)	13.0	3.0	10	1.9	1.4	0.9	1.0	15	10.2
Wethersfield	12.0	1.0	1	1.9	2.3	0.9	0.4	10	11.1
Holyoke (Conn.)	10.0	3.0	8	2.6	1.4	1.5	0.7	11	13.0
Dekalb[2] (W. Va.)	6.0	7.0	3	2.7	1.2	1.1	0.6	13	18.0
Lordstown[2] (N.Y.)	10.0	12.0	15	1.4	1.2	1.0	0.3	6	13.6
Mardin[2] (N.Y.)	6.0	6.0	17	1.6	0.8	1.0	0.5	6	20.5
Average	9.5	5.3	9	2.0	1.4	1.1	0.6	10	14.4

Data from Soil Survey Laboratory (1952) unless otherwise indicated.

[1] Unpublished data, Soil Survey Laboratory.

[2] Data from Soil Survey Laboratory, Baur and Lyford (1957).

Forest soils despite their low base saturation, but they are grouped here with the Brown Podzolic soils on the evidence cited earlier that they formerly had a thin bleicherde.

From these data it would seem that the development of the B horizon in the soils called Podzols is on the average somewhat stronger than in the soils called Brown Podzolic, although there is a considerable overlap. The weaker development of the B in the Brown Podzolic soils could be in part due to mixing of the B with the A and, in some cases, with a part of the C. There is a possibility, too, that some of the soils called Brown Podzolic soils were Sol Brun Acide with very thin Podzols developed in the A horizons.

Analyses of the clay fraction of two Podzols and a Brown Podzolic soil formed from a granitic drift in New England were reported by Brown and Byers (1938). Their data on the SiO_2/R_2O_3 ratios follow:

SiO_2/R_2O_3 Ratios

	A	B	C
Podzol (Hermon)	2.21	0.58	0.97
Podzol (Brassua)	2.99	0.68	1.53
Brown Podzolic (Gloucester)	2.00	0.64	1.97

These data again emphasize the fundamental similarities of the Brown Podzolic soils to the Podzols. The C/N ratio of the B_2 of the Gloucester was 18, of the Brassua 38, and of the Hermon 32.

Lunt (1932) reports carbon-nitrogen ratios of Podzols in New England as averaging about 27 in the B horizons of moderate and strong Podzols. In his "mull type" soil, which the authors interpret to be Brown Podzolic soils, the carbon-nitrogen ratios of the B horizons average about 18.

The data show some consistent differences between the Sol Brun Acide or Acid Brown Earth profiles and the Brown Podzolic and Podzol profiles. Clay contents of the (B) of the Sol Brun Acide profiles are higher, organic carbon is lower, the carbon-nitrogen ratios are narrower, the soils are appreciably thicker despite their finer texture, and evidences of iron translocation are very weak or absent. There is, however, more free iron in the (B) than in the C, indicating appreciable weathering.

Both the laboratory data and the field observations indicate that the Brown Podzolic soils are related to the Podzols, but distinct from the soils having a (B). The distinction then between the soils having a (B) and the Brown Podzolic soils is as fundamental as the distinction between the soils having a (B) and the Podzols. The visible morphologic differences, however, between the Brown Podzolic soils and the Sol Brun Acide are obscure.

In the Scandinavian countries the Brown Podzolic soils have been called, almost without exception, Brown Earth. They also correspond to Stremme's "Nicht oder schwach gebleichter rostfarbene Brauner Waldboden" (unbleached rusty colored Brown Forest soil), and in part to the "Podzolic Brown Forest soil" of Laatsch and the Podzolic Braunerde of Muckenhausen, and very probably to the Kryptopodzolic and Stesopodzolic Braunerde subdivision of the Podzolic Braunerde of Kubiena. It should be noted that other soils than Brown Podzolic are included in the Podzolic Braunerde. The name Podzolized Brown Forest soils also seems to have been used. In England the Brown Podzolic soils generally have been called Brown Earths of low base status, but recently Avery (1956) has introduced the name "Podzolic Brown Earth." In France they have mostly been called simply Sols Bruns, but in 1956 Aubert and Duchaufour used the name "Sols Bruns podzoliques." They also seem to correspond to the (typical) Acid Brown soils of Cernesco (1956) and Chiritza (1956), and to the Cryptopodzolic Brown Earth (Musiërowicz, 1954). Undoubtedly, other names have been used.

The Brown Podzolic soils of the United States were placed by Marbut (1927) in the Brown Forest group, and later (1931, 1936) in the Gray-Brown Podzolic class. The first recognition that the Brown Podzolic soils were different from the Gray-Brown Podzolic soils was by Baldwin *et al.* (1938). Their definition of the Brown Podzolic soils was broad enough to include soils with a (B) such as the Sol Brun Acide, and the Brown Podzolic soils of the eastern states were not distinguished from the Sol Brun Acide until 1954 (Bourbeau and Swanson). In the far western states the soils called Brown Podzolic generally did not include other kinds of soils.

Profiles belonging to the Brown Podzolic group can be found in many European countries. The following profile description was made of a soil just west of Lillesand, Norway. The vegetation was mostly oak with some birch and pine, and a ground cover of a little calluna with considerable grass. The slope was about 3 to 4 per cent, and the parent material presumably a marine shale.

The profile was:

Horizon	*Inches*	*Description*
A_{00}	1–0	Partially decomposed oak leaves.
A_1	0–1½"	Very dark brown (10YR 2.5/2) moist, silt loam, very friable with strong medium crumb structure and abundant roots; abrupt smooth lower boundary.
B_{21}	1½–9	Dark brown (7.5YR 3/4) moist, silt loam, very friable; the finger can be pushed into the horizon with little resistance, indicating a low bulk density; massive breaking to weak very fine crumbs, smooth gradual lower boundary.

Horizon	Inches	Description
B_{22}	9–21	Dark brown to brown (7.5YR 4/4) moist, silt loam, massive, friable removed but firm in place as though with higher bulk density, abrupt, irregular lower boundary.
C_1?	21–25	The profile was not examined below 30 inches, and the horizon designation is uncertain. Gray and grayish-brown (10YR 5/1 and 5/2) blocky, very firm to extremely firm silt loam. It appears to be a fragmented marine deposit. The blocks are rounded, average perhaps ½ to 1 inch in diameter, and occupy about 50 to 75 per cent of the mass. The material between the blocks is the same as that in the overlying horizon.
C?	25–30+	Similar to above, but blocks are larger, 1 to 3 inches in diameter and occupy over 95 per cent of the mass.

Another profile from Italy is described below to indicate the similarities. This profile was described on a steep slope with over 50 per cent gradient, near Ponte Sesteione, about 35 miles northwest of Florence. The elevation was about 850 m., mean annual temperature about 8° C., and rainfall about 2075 mm. The climate, therefore, is not greatly different from that at Lillesand, Norway. The vegetation was dominantly chestnut, with some bracken fern and pine. The parent material was sandstone. The profile was:

Horizon	Inches	Description
A_{00}	1½–½	Partially decomposed chestnut leaves.
A_0	½–0	Mixture of well-decomposed leaves and coprogenic material, a mor.
A_1	0–1	Very dark brown (7.5YR 3/2) moist, loam having a low clay content, very friable; strong fine crumb structure, most sand grains in this horizon are bleached, that is, lack coatings visible with a hand lens; under the hand lens the quartz grains glisten like pearls; lower boundary is smooth and abrupt; pH is about 5.0.
B_{21}	1–4	Dark-brown (7.5YR 3/4) moist, loam with about same clay content as in A_1; structure is a mixture of about half firm to very firm rounded aggregates, ⅛ to ¼ inch in diameter, with balance of horizon nearly massive but breaking to very fine crumbs, and friable to very friable; there are a few bleached sand grains throughout; roots are abundant; clear smooth lower boundary.
B_{22}	4–30	Strong brown (7.5YR 4/6) moist, stony loam with about the same clay content as horizon above; structure is nearly massive but breaks to weak fine and medium crumbs, consistence is very friable; and finger can be pushed into the horizon with little resistance; all sand grains are coated; roots are abundant; pH is about 6.0. The base of the pit was at 30 inches, but the sandstone lies not far below.

A similar profile was studied during the excursions organized during the First Meeting of the Subgroup for Soil Classification and Survey in Europe of F.A.O. in Ghent in 1954. The following names were given to the soil by the participants:

Dr. J. Läg (Norway)—Very weakly developed Podzol with raw humus with high degree of activity.

Dr. D. Osmond (England) and Dr. R. Glentworth (Scotland)—Brown Forest soil of low base status.

Dr. J. Bennema (Netherlands) and Dr. P. Stobbe (Canada)—Brown Podzolic.

Common variants of the Brown Podzolic profiles described above are similar in the A and B, but may be underlain by a fragipan at about 20 to 40 inches, or may be underlain first by an horizon of eluviation of silicate clays, and below that by a B horizon of clay accumulation. The authors have seen Brown Podzolic profiles with fragipans from Scotland and Norway to Italy and Yugoslavia.

In the United States the Brown Podzolic soils are common in southern New England, the Appalachian highlands, and the Allegheny plateau, and a few are found in the northern parts of Michigan and Wisconsin and in the northeastern part of Minnesota. In the western part of the United States the soils are common in the mountains and extend down to near sea level along the coast in Oregon and Washington. In general, both in Europe and the United States, the Brown Podzolic soils are more common under the broadleaf deciduous trees, such as maple, oak, and aspen, than under the conifers. There are important exceptions to this statement, particularly in the western part of the United States, where the soils commonly occur under fir, hemlock, and cedar. The map, Figure 1, shows areas where the Brown Podzolic soils are dominant, though they occur commonly on acid parent materials with low clay contents throughout the areas of occurrence of the Sol Brun Acide.

3. *Dark Colored Soils Bordering the Steppes*

The soils of this class typically have thick dark A horizons. The dark colors commonly extend down to the B horizon, and the B horizon is usually dark or very dark, has brown coatings on the peds, and is typically an horizon of clay accumulation.

These soils occur at the margins of the steppes where there has been a recent invasion by the forest. Murgoci (1909) has pointed out in Europe that there has been an invasion of the steppes by the forest. In the United States evidences for a similar spread of the forest were summarized by Smith *et al.* (1950) for the region of Prairie soils.

In Europe these soils have been included in the Brown Forest soils by Murgoci (1909), Stebutt (1930), and Chiritza (1956). Glinka and many others have called them Degraded Chernozems. Florow (1924) has described these soils as "Humus-rich Forest Steppe soil."

The morphologic changes in the Prairie soils following an invasion of the forest were described by Smith *et al.* (1950) as follows:

"A few sites still remain where a dense mature forest, chiefly elm, oak and hickory, is growing on soils which are indistinguishable in the field from the adjacent Prairie soils. Starting in such an area and studying the morphological changes in the soil with distance toward the nearest area of Gray-Brown Podzolic soil, it is often found that the changes are more or less continuous over a distance of one-sixteenth to one-quarter mile. The first perceptible morphologic change from the Prairie to the Gray-Brown Podzolic soil is either an increase in the degree of development of the structural aggregates in the B horizon in the well-drained soils or the appearance of light and then heavy gray coatings in the lower part of the A horizon of moderately well-drained soils. The most rapid decrease in organic matter seems to occur in the lower part of the A horizon where the normal differences between Prairie and Gray-Brown Podzolic soils are greatest. The next stage is the development of the Gray-Brown Podzolic A_1 and A_2 horizons overlying a B horizon which has nearly the normal color for the Prairie soils. Following this the organic content decreases in the upper part of the B horizon. The most persistent evidence of a former prairie vegetation is the presence of organic coatings on the structural aggregates in the lower part of the B horizon."

Shrader (1950) compared Gray-Brown Podzolic and Prairie soils formed from loess. He found that, with comparable clay contents in the B horizons, the Gray-Brown Podzolic soils had roughly half as much clay in the A as the Prairie soils. The transitional or Degraded Prairie soils were intermediate in character but were more like the forest soils. White and Riecken (1955) studied a variety of properties of two Brunizems, their Gray-Brown Podzolic equivalents, and the intergrades. The intergrades were truly intermediate in all properties studied, but were in general more closely related to the Gray-Brown Podzolic soils than to the Bruinzems. It should be noted that they selected profiles of Degraded Brunizems which showed some visible evidence of change under the forest.

The invasion of the Chernozems, Brunizems, Reddish Prairie, and Chestnut soil areas by forest seems to have taken place on both continents. The Degraded Chernozems were recognized as a great soil group by Dokuchaiev (1886) and by most subsequent authors. However, the Degraded Brunizems, Reddish Prairie, and Chestnut soils

have not been given a comparable status. It is apparent from the literature review that these have been considered Brown Forest soils or Braunerde by many authors. Simonson *et al.* (1952) considered that the Degraded Brunizems (Prairie soils) should be placed either with the Brunizems or Gray-Brown Podzolic soils, according to an arbitrary but generally agreeable boundary, but should be recognized as intergrades between the two great soil groups. An intermediate great soil group was not considered any more necessary than intermediate groups between the Brunizems and the Humic-Gley soils or other great soil groups which have common boundaries with the Brunizems.

In the western states, the name Brown Forest soils has been used by Cheney *et al.* (1956) and in the mimeographed soil series descriptions of the Soil Survey.

Recently, the name Rubrozem has been proposed by Bramao and Simonson (1956) for a group of soils which will be discussed below.

Several varieties of the dark-colored soils bordering the steppes can be distinguished, though sometimes only by laboratory analyses. These are as follows:

a. The Northern Degraded Chernozems and Degraded Black Soils. Degraded Chernozems in the United States and Degraded Black soils in Canada have been recognized along the border of the Chernozems of the United States and the Black soils of Canada with the Gray Wooded soils. The following profile description and laboratory data are given by the Soil Survey Laboratory (1952).

Waukon silt loam

Samples were taken along a deep road cut in a strongly morainic area from the top of a rather high ridge on a 4 to 5 per cent slope underneath a cover of oak and brush. Vegetation consists largely of red oak trees, with hazel, sumac, Juneberry shrubs, and grass.

Horizon	*Inches*	*Description*
A_1	0–7	Very dark brown (10YR 2/2) silt loam; well-developed fine granular structure; very friable; abundant roots. Upon drying, white silica grains become evident. Mildly alkaline.
A_2	7–10	Dark gray (10YR 4/1) silt loam; weakly developed coarse platy structure in place, breaking into fine granules which crush to yellowish-brown (10YR 5/6); roots numerous; pebbles few. Neutral.
A_3	10–13	Dark gray brown (10YR 4/2) silty clay loam; moderately developed subangular blocky structure, with light gray and white coatings on the aggregates, few organic and iron stains. Roots numerous, but less than in layer above. Very slightly acid.

Horizon	*Inches*	*Description*
B_{21}	13–20	Brown (10YR 5/3) heavy silty clay loam. Well-developed medium blocky structure; blocks mottled with very dark brown (10YR 3/2); few roots; few pebbles; slightly acid.
B_{22}	20–25	Yellowish-brown (10YR 5/4) heavy silty clay loam, streaked with very dark brown (10YR 2/2). Well-developed coarse blocky structure; blocks are very firm and are coated with a few white, noncalcareous spots. Roots moderate; pebbles few; mildly alkaline. This layer is slightly prismatic in place.
B_3	25–32	Light yellowish-brown (10YR 6/4) silty clay loam, streaked with very dark brown (10YR 2/2). Well-developed very coarse blocky structure, the aggregates slightly coated with white specks. Many small pebbles; roots numerous; several old root channels; calcareous. This layer is slightly prismatic in place.
C_{ca}	32–42	Pale brown (10YR 6/3) and white (10YR 8/2), specked with strong brown (7.5YR 5/8) silty clay loam; massive; many reddish-yellow iron stains; few pebbles of granitic and dolomitic origin; few tap roots; highly calcareous.
	42–54	This is a transitional layer, not sampled.
C_2	54–64	Pale yellow (2.5Y 8/4), spotted with brownish-yellow (10YR 6/8) light clay loam; massive; highly calcareous, lime segregations feathering out in all directions, at places weblike. Few iron segregations; few pebbles, largely granitic and dolomitic; few shale fragments. Moderately compact in place, easily friable when removed.

Waukon silt loam

Horizon	Depth (inches)	Particle size distribution (in mm.) per cent: Very coarse sand 2–1	Coarse sand 1–0.5	Medium sand 0.5–0.25	Fine sand 0.25–0.10	Very fine sand 0.10–0.05	USDA silt 0.05–0.002	Clay <0.002	Int. silt 0.02–0.002
A_1	0–7	2.8	6.4	20.0	9.5	10.4	29.6	21.3	17.4
A_2	7–10	2.9	6.8	8.3	24.2	12.5	26.8	18.5	15.0
A_3	10–13	—	—	—	—	—	—	—	—
B_{21}	13–20	4.0	5.3	6.5	17.4	10.9	26.7	29.2	15.3
B_{22}	20–25	2.6	5.5	6.8	17.4	10.7	26.4	30.6	15.6
B_3	25–32	—	—	—	—	—	—	—	—
C_{ca}	32–42	—	—	—	—	—	—	—	—
C_2	54–64	2.2	5.5	6.7	18.7	12.8	33.2	20.9	19.2

Horizon	Depth (inches)	pH	Organic carbon (%)	Cation exchange capacity (meq./100 g.)	Extractable cations (meq./100 g.) Ca	Mg	H	Na	K	Base sat. (%)
A_1	0–7	7.1	5.2	34.1	19.0	10.0	4.2	<0.1	0.9	88
A_2	7–10	7.0	2.16	23.1	15.6	3.6	3.3	<0.1	0.6	86
A_3	10–13	—	—	—	—	—	—	—	—	—
B_{21}	13–20	6.0	0.34	21.8	12.4	4.3	4.7	<0.1	0.4	78
B_{22}	20–25	6.8	0.45	31.6	19.1	9.7	2.5	<0.1	0.3	92
B_3	25–32	—	—	—	—	—	—	—	—	—
C_{ca}	32–42	—	—	—	—	—	—	—	—	—
C_2	54–64	7.6	0.14	26.2	19.1	6.9	0	<0.1	0.2	100

The description and data show distinct clay accumulation in the B. The lack of coatings on the sand grains in the A horizon is characteristic of the northern varieties of Chernozem or Black soils, the Gray Wooded soils, and the associated Degraded Chernozems.

b. The Degraded Brunizems (Prairie Soils) and Reddish Prairie Soils. These differ from the Degraded Chernozems or Degraded Black soils chiefly in the warmer temperatures and the common coatings on the sand or silt particles giving the A horizons a browner color.

c. The Degraded Chestnut Soils. In the western part of the United States rainfall increases with elevation, and one may pass from the desert through the Sierozem and Brown zones and into the Chestnut zone before reaching the forest. The boundaries between the prairie and forest usually have a park vegetation, with grass and scattered trees or clumps of trees. Finally, one passes through the park vegetation into the forest. The profiles of the Chestnut soils continue with few or no visible changes through the park, and in the forest one still can find soils with the appearance of the Chestnut soils. These soils with the thick dark A_1 horizons, resembling the Chestnut soils, have generally been called Brown Forest soils in the published soil series descriptions and regional maps (Cheney *et al.*, 1956). No published studies of the relation of the soils with the associated steppe and forest soils are known to the authors, but several profiles of these Brown Forest soils were reported by the Soil Survey Laboratory (1952). A representative profile description of Segal stony gravelly sandy loam, with the laboratory data, follows.

Segal stony gravelly sandy loam

Horizon	*Inches*	*Description*
A_0	1–0	Very dark grayish-brown (10YR 3/2) loose mat of decayed and partially decayed pinon needles. Some fungi, which appear to accumulate in local areas or nests. Rests directly on

Horizon	*Inches*	*Description*
A_{11}	0 2	Dark grayish-brown (10YR 4/2; very dark grayish-brown, 10YR 3/2, moist), loose, gravelly, friable sandy loam, very slightly plastic. Noticeable amount of loose, slightly decomposed gravels and angular chips on the surface and in this horizon. Also some angular cobbles 5 inches or larger. Rocks are fine-grained, crystalline, and consist of feldspar, quartz, and hornblende. The rocks look very old. Roots not particularly noticeable. Gradual change to
A_{12}	2–4	Grayish-brown (10YR 5/2; very dark grayish-brown, 10YR 3/2, moist), weak, granular, gravelly sandy loam. The granules are very thinly coated with gray siliceous material indicating a slight tendency for an A_2 development. This layer may be considered to be a perched water table. This seems to be the layer of greatest root concentration. Gradual change to
B_1	4–10	Dark-brown (10YR 4/3; dark brown, 10YR 3/3, moist), firm, granular, slightly plastic gravelly loam. This layer is contrasting in color and texture to layer above. Roots plentiful, some 1/16 inch in diameter. This layer may be an A_3 layer rather than a B_1. Abrupt change to
B_{21}	10–16	Brown (10YR 4/3; dark brown, 10YR 3/3, moist), dense, plastic, sticky gravelly clay. Structure appears to be ill-defined prismatic or blocky. Very few roots. Not so many gravels as in layer above, but more undecomposed minerals. Gradual change to
B_{22}	16–27	Yellowish-brown (10YR 5/4; dark yellowish-brown, 10YR 4/4, moist) gravelly clay loam with no distinct structure. to cloddy. Soil appears massive, dense, and compact. Considerable unweathered gravel and sharp angular particles. Gradual change to
B_3	27–32	Yellowish-brown (10YR 5/4; dark yellowish-brown, 10YR 4/4, moist) gravelly clay loam with no distinct structure. Moderately plastic, very few roots, lots of undecomposed minerals. Gradual change to
C	32–39+	Mottled pale brown (10YR 6/3) and yellowish-brown (10YR 5/4) partially decomposed gravelly clay loam or heavy loam. The lighter color materials appear to be the least decomposed and have the color of unweathered gravels.

"The color and texture indicate that this is a strongly developed soil, probably a maximal or claypan 'Brown Forest' of the west. It has a slight tendency to have a perched water table above the B horizon. According to color it is comparable to many of the Chestnut soils, but it is timbered or partially so. It is doubtful, however, if the trees have had a very significant effect on the soil profile. Free lime does not occur in the profile, but this is probable because of the kind and age of the parent material. The pH is about 6.5 in all layers. All layers

react with H_2O_2 but layers 2, 3, 4, and 5 react the longest. Aggregates to a depth of 10 inches are fairly stable in water, but below this depth they slake readily when immersed in water. This is a typical sample of a strongly developed profile of the so-called 'Brown Forest' of the intermountain region."

Segal stony gravelly sandy loam

Horizon	Depth (inches)	Particle size distribution (in mm.) per cent: Very coarse sand 2–1	Coarse sand 1–0.5	Medium sand 0.5–0.25	Fine sand 0.25–0.10	Very fine sand 0.10–0.05	USDA silt 0.05–0.002	Clay <0.002	Int. silt 0.02–0.002
A_0	1–0	—	—	—	—	—	—	—	—
A_{11}	0–2	19.4	25.6	12.0	14.4	6.6	14 5	7.5	9.4
A_{12}	2–4	23.7	23.6	10.4	12.3	5.8	15.4	8.8	10.0
B_1	4–10	16.6	20.7	10.5	14.5	8.1	16.6	13.0	10.2
B_{21}	10–16	14.9	16.4	7.7	10.4	6.1	17.6	26.9	11.1
B_{22}	16–27	17.2	11.9	4.6	6.8	4.8	18.8	35.9	12.7
B_3	27–32	11.4	12.2	6.9	10.2	6.4	17.6	35.3	11.1
C	32–39+	12.0	14.8	8.5	14.3	9.0	21.6	19.8	12.9

Horizon	Depth (inches)	pH	Organic carbon (%)	Cation exchange capacity (meq./100 g.)	Extractable cations (meq./100 g.): Ca	Mg	H	Na	K	Base sat. (%)
A_0	1–0	4.6	—	—	—	—	—	—	—	—
A_{11}	0–2	6.6	1.72	10.4	5.6	1.0	2.7	0.3	0.8	74
A_{12}	2–4	6.8	1.07	11.0	6.8	1.4	2.0	0.1	0.7	82
B_1	4–10	6.6	0.69	12.5	7.4	1.8	2.7	0.1	0.5	78
B_{21}	10–16	6.3	0.78	18.5	11.3	3.8	2.5	0.4	0.5	86
B_{22}	16–27	6.1	0.61	26.4	15.5	5.8	4.3	0.4	0.4	84
B_3	27–32	6.2	0.37	28.1	16.4	6.7	4.2	0.4	0.4	85
C	32–39+	6.3	0.26	23.9	14.8	5.9	2.7	0.3	0.2	89

It will be evident that this soil has a strongly developed illuvial B horizon, and that it does not fit the requirement in the definition of Brown Forest soils that there be little or no illuviation of iron or alumina in the B.

d. The Rubrozems. The name Rubrozem was proposed by Bramao and Simonson (1956) for a group of soils with some morphological features of Chernozems and others of Red-Yellow Podzolic soils. The soils

have thick black to very dark-brown A horizons lying on red to strong brown B horizons of fine texture. Thus, they look as though the A horizons of typical Chernozems had been placed on top of the B and C horizons of Red-Yellow Podzolic soils. The data they present show a high organic matter content in the A, an illuvial B horizon with clay accumulation, and very low base saturation.

Among the profiles of Brown Forest soils the authors have seen in Europe, there are a number which would be grouped with the soils having thick dark A horizons. It is probable from the literature that all the varieties described above occur in Europe, but the authors have first-hand knowledge of only two. These were seen in Yugoslavia.

One such profile was seen at the edge of Mladenovac, a little south of Belgrade. It lay on about a 15 per cent slope, and the authors presume that it was formed in loess or in a reworked loess. The profile was described as follows:

Horizon	*Inches*	*Description*
Ap or A_1	0–7	Very dark grayish-brown (10YR 4/2 dry, 3/2 moist) silty clay loam, very hard when dry, plastic when wet; weak coarse to medium granular structure; common worm casts; smooth lower boundary.
A_3	7–10	Very dark grayish-brown (10YR 4/2 dry, 3/2 moist) heavy silty clay loam, mostly like A_1, but there are a few browner worm casts from the B; worm casts abundant; moderate fine granular structure; smooth lower boundary.
B_1	10–14	Dark brown when rubbed (10YR 5/3 dry, 3.5/3 moist); a mixture of B_2 with abundant dark worm casts from A_1; clear lower boundary.
B_2	14–34	Dark brown (10YR 5/3 dry, 3.5/3 moist) heavy silty clay, medium to coarse subangular blocky structure, breaking to fine and very fine angular blocky peds; continuous clay skins; extremely hard when dry; very plastic and sticky to very sticky when wet; a few dark worm casts; roots common. The face of the cut has cracked into very coarse prisms; clear smooth lower boundary.
Cca	34–72	Dark yellowish-brown (10YR 4/4, moist) heavy silty clay loam or light silty clay; very many segregations of white secondary lime in pin holes and worm holes; few worm holes filled with dark material; nearly massive; very hard when dry; plastic and sticky when wet.
	72+	A dark buried soil, with much segregated secondary lime.

The pH is about 7.0 or more in the entire profile.

The landscape here is similar to parts of Oklahoma where the scrub oak has spread in recent years. The profile above actually shows no visible evidence of degradation, and in the United States would have

been considered either a Brunizem, a Reddish Prairie, or Reddish Chestnut soil.

A soil which probably should be grouped with the Rubrozems, formed from limestone, was seen near Generalski Slot west of Zagreb. This area had been invaded by *Calluna vulgaris*. It showed many small sink holes and had many limestone outcrops. The A_1 horizon was a very dark-brown (10YR 2/2, moist) heavy silt loam which graded into a dark yellowish brown (10YR 4/4) B with distinct evidences of clay accumulation. The texture of the upper part of the B was either a heavy silty clay loam or light silty clay. The lower part of the B rested directly on the limestone, had a heavy clay texture, and was distinctly darker than the upper part of the B.

The general areas of occurrence of these soils, class 2, in the United States and western Europe, are shown in Figure 1.

The authors have no first-hand information on the distribution in Europe of the soils of class (*a*), the northern Degraded Chernozems or Degraded Black soils. Probably they never have been called Braunerde. They might correspond to the subtype of the Chernozems called Podzolic Chernozem by Gerassimov. The soils of class (*b*), the Degraded Brunizems or Reddish Prairie soils, and of class (*c*), the Degraded Chestnut soils, have been called Brown Forest soil among others by Stebutt (1930). They seem to occur quite generally on the hilly regions of the Balkan, characterized by a climate that is transitional between the Mediterranean and the Southern Steppe. But it should be emphasized again that the authors have only a very limited knowledge of this area. The soils of class (*d*), the Rubrozems, seem to occur only in relatively small areas in the same climatic environment as the soils of classes (*b*) and (*c*). In Yugoslavia they have been called "Degraded Brown Earth" and also "Heather soils," according to Neugebauer and Vovk (1956).

In the United States, the soils of class (*a*), the northern Degraded Chernozems or Degraded Black soils, are found chiefly in northwestern Minnesota, and a few small areas may occur throughout the mountains in the western states. A broad belt of these soils is found at the northern margin of the Great Plains in western Canada. This belt has been described by Mitchell and Moss (1948).

The soils of class (*b*), the Degraded Brunizems and Reddish Prairie soils, occur throughout the zone of occurrence of the Brunizems and Reddish Prairie soils. Generally, the areas are small and border the hilly areas either along the streams or along the moraines in the glaciated sections. They are therefore widely scattered small areas, beginning with a few scattered areas in Ohio, and increasing in frequency across northern Indiana. The most common occurrence is in northern

Illinois, southern Wisconsin, eastern Iowa, southeastern Minnesota, and western Missouri. In western Iowa and eastern Nebraska and Kansas the areas are few. In the Reddish Prairie area, in southeastern Kansas, eastern Oklahoma, and parts of Texas, the soils showing visible evidences of degradation are minor. There are extensive areas having a recent invasion of brush where the soils seem comparable to some of the European Brown Forest soils. These areas are in southwestern Missouri and along the eastern border of Oklahoma.

The soils of class (*c*), the Degraded Chestnuts, are common in the mountains in the western states, but are not known elsewhere. Although the general area of occurrence is extensive, individual areas are generally small and occupy only a small percentage of the landscape.

The soils of class (*d*), the Rubrozems, are of very minor extent in the United States, if indeed they occur.

4. *Gray-Brown Podzolic Soils, and Related Great Soil Groups Having an Illuvial B Horizon of Clay Accumulation*

This is certainly the most extensive of the possible classes of Braunerde and Brown Forest soils. Included here are the Gray-Brown Podzolic soils, the Noncalcic Brown soils, and some members of the Red-Yellow Podzolic group with brown B horizons.

a. Gray-Brown Podzolic Soils. It was pointed out earlier that Baldwin (1927) proposed this name for a group of soils having a blocky illuvial B horizon of clay accumulation. His definition was adequate to distinguish the soils from those later called Gray Wooded and Sol Brun Acide, but the distinction between the Gray-Brown Podzolic soils and the Noncalcic Brown soils had not been made clear except in terms of the climates in which they are found. Because the Noncalcic Brown soils of the United States are geographically remote from the Gray-Brown Podzolic soils, there has been little confusion in the classification. Likewise, there has been no clear distinction made between the Gray-Brown Podzolic soils and those members of the Red-Yellow Podzolic group with brown B horizons except in general climatic terms. The Red-Yellow Podzolic soils, however, are adjacent to or even intermingled with the Gray-Brown Podzolic soils, and the basis for the distinction has been vague.

Marbut (1927) drew a boundary between the Brown Forest and the Red soils on the Atlantic Coastal Plain and Piedmont roughly along the Virginia-North Carolina boundary. He stated (1928) that the "line is located at that place because it marks the northern limit of the region in which the iron accumulation has become so great that it consists not merely of colloidal material in the B horizon of the soils but has accumulated to an extent as segregated iron." In terms of the

junior author's observations, this approximates the boundary of occurrence of concretionary or pisolitic laterite in the soils, but it is not clear that Marbut had this in mind. In later lectures he mentions the pisolites as an inheritance from a former weathering cycle. In 1936 he moved this boundary slightly to the north, or to about the middle of Virginia. Soils to the south of that line were called Red-Yellow Podzolic and to the north of the line Gray-Brown Podzolic.

Whatever Marbut's basis was for the boundary he drew, it was the boundary itself which became the main distinction between Gray-Brown Podzolic and Red-Yellow Podzolic soils. Few soil series crossed this boundary.

Brown and Byers (1938) pointed out that the Chester series of Maryland and Pennsylvania, although placed in the Gray-Brown Podzolic group, is more like many Red-Yellow Podzolic soils.

Since Miami silt loam was considered the "type" Gray-Brown Podzolic soil, a description, together with the data, is given below as reported by Brown and Thorp (1942). Munsell color values have been added by the authors from recent profile descriptions of the Miami series.

Horizon	*Inches*	*Description*
A_1	0–2	Very dark brownish-gray (10YR 4/2, moist) soft fine granular or crumblike silt loam containing much organic matter that has been intimately mixed with the mineral soil by worms, insects, and small mammals. It is a true granular mull. Numerous rodent and mole burrows follow this horizon immediately beneath the thin mat of decaying dead leaves. Fibrous feeder roots of trees and underbrush are abundant. The color is much lighter when the soil is dry.
A_2	2–5	Light brownish-gray (10YR 5/3, when moist), fading to very light brownish-gray when dry, silt loam containing worm burrows filled with dark soil from the A_1 horizon. This horizon grades into those above and below with an inch or two of transitional material in each case. The soil is friable and of phylliform (thin platy) structure and breaks into thin, easily crushed flakes. There are many small roots and a few large ones, but the feeder roots are less abundant than in the A_1.
A_3	5–11	Pale yellowish-brown or brownish-yellow (10YR 5/3, when moist), friable silt loam with faint streaks of light brownish gray from the horizon above. This breaks into easily crumbled plates about 1/16 inch thick. Feeder roots considerably less abundant than in A_1 and A_2. This grades almost imperceptibly into the next horizon.
B_1	11–15	Light yellowish-brown (10YR 5/3, when moist) friable heavy silt loam, breaking into plates about 1/16 inch thick in the upper part and into somewhat flattened subangular

Horizon	*Inches*	*Description*
		nuciform (nut-shaped) aggregates ¼ to ½ inch in diameter in the lower part. A few large and small roots pass through this horizon. There is a tendency for slight variegation in color owing to penetrations of lighter colored material from above and to thin brown colloidal accumulations on the surfaces of the structural aggregates, especially in the lower part.
B_2	15–30	Yellowish-brown (10YR 4/3 to 5/4, when moist) clay loam breaking into small, somewhat rounded granular and nuciform aggregates from ¼ to ¾ inch in diameter. The surfaces of the aggregates and the walls of root holes and cracks are coated with brown and dark-brown colloidal material probably carried down from upper horizons. The boundary between this and the next horizon varies from clear to diffuse and occurs at variable depths.
B_3	30–36	Dark-brown (10YR 3/4, when moist) rather sticky clay loam with a slightly reddish tint, breaking into angular blocky aggregates ½ to ¾ inch in diameter. The dark color is more or less concentrated in streaks and coatings, and the material is much lighter colored when pulverized. The horizon contains many fragments of more or less disintegrated rock fragments. The boundary between the B_3 and C_1 is sharp but varies locally in depth.
C_1	36+	Olive-gray (10YR 5/3, when moist) glacial till of loam texture composed of a large percentage of limestone and dolomitic limestone fragments and a smaller percentage of other sedimentary and igneous rocks of highly diverse character. The till includes a rather high percentage of rock flour and some clay. Some of the larger tree roots extend well into this parent rock.

Data on base saturation are not available for this profile, but other profiles of Miami consistently show base saturation over 60 per cent in the B_2.

One common variant of the typical Gray-Brown Podzolic profile described above includes soils with a well-developed fragipan at 20 to 40 inches, and with either heavy bleached silt coatings on the ped surfaces of the B above the fragipan, or with a distinct bleached horizon of eluviation between the B and the fragipan. Where this latter horizon occurs, it tongues into or interfingers with the B above, as though the B were being destroyed, and there may be a thin horizon of clay accumulation from 3 to 6 inches thick just above the fragipan.

Another common variant includes soils in which the A_2 horizon tongues into the B from above. In extreme cases, the tongues of gray A_2 may extend through the B and terminate at a much lower horizon of clay accumulation. If these profiles are virgin, they usually have a very thin, ½ to 2 inch brown horizon at the surface and sometimes

Chemical analyses of Miami silt loam

Horizon	Depth (inches)	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	MgO (%)	CaO (%)	K_2O (%)	Na_2O (%)	TiO_2 (%)	MnO (%)	P_2O_5 (%)	SO_3 (%)	Ignition loss (%)	Total (%)	Org. matter (%)	CO_2 (%)	N (%)
A_1	0–2	74.00	3.28	8.39	0.84	0.90	1.83	0.90	0.83	0.13	0.35	0.23	8.32	100.00	6.22	0.03	0.28
A_2	2–5	77.81	2.90	9.18	0.83	0.54	1.99	1.06	0.68	0.14	0.09	0.09	5.28	100.59	3.60	0.13	0.20
A_3	5–11	78.45	3.25	9.57	0.80	0.70	1.97	1.18	0.68	0.13	0.08	0.07	3.70	100.58	1.95	0.09	0.11
B_1	11–15	76.10	4.05	11.01	1.00	0.60	2.05	1.05	0.71	0.12	0.08	0.07	3.56	100.40	1.37	0.21	0.08
B_2	15–30	69.80	6.23	14.23	1.42	0.62	1.75	0.68	0.62	0.11	0.07	0.07	4.28	99.88	0.99	0.11	0.05
B_3	30–36	69.00	6.32	13.99	1.63	0.98	2.28	1.00	0.59	0.12	0.14	0.09	4.36	100.50	1.11	0.16	0.07
C_1	36+	53.66	4.52	9.99	5.79	8.99	1.93	0.74	0.46	0.09	0.09	0.09	13.99	100.34	0.99	11.28	0.03

Mechanical analyses of Miami silt loam

Horizon	Depth (inches)	Gravel +2 mm. (%)	Fine gravel 2–1 mm. (%)	Coarse sand 1–0.5 mm. (%)	Medium sand 0.5–0.25 mm. (%)	Fine sand 0.25–0.1 mm. (%)	Very fine sand 0.1–0.05 mm. (%)	Silt 0.05–0.002 mm. (%)	Clay 0.002–0 mm. (%)	Clay 0.005–0 (mm.) (%)	pH	Iron oxide concretions (%)
A_1	0–2	—	1.1	3.7	5.2	11.7	6.2	50.1	15.9	23.6	6.3	2
A_2	2–5	—	1.2	3.8	5.7	12.6	6.7	50.9	15.5	23.9	5.9	2
A_3	5–11	—	1.3	3.8	5.7	12.7	7.1	51.1	16.4	25.0	5.5	2
B_1	11–15	—	1.7	3.9	5.4	12.3	6.8	45.9	22.7	30.8	5.5	2
B_2	15–30	10	1.9	5.1	6.5	12.5	7.4	28.9	36.9	42.9	5.2	2
B_3	30–36	<10	3.2	5.9	6.5	13.0	7.4	25.7	37.4	42.6	6.4	4
C_1	36+	10	4.3	6.7	6.5	13.6	9.9	37.1	21.3	27.6	7.6	3

Chemical analyses of Miami silt loam colloid

Horizon	Depth (inches)	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	MgO (%)	CaO (%)	K_2O (%)	Na_2O (%)	TiO_2 (%)	MnO (%)	P_2O_5 (%)	SO_3 (%)	Ignition loss (%)	Total (%)	Organic matter (%)	CO_2 (%)	N (%)
A_1	0–2	41.52	8.84	21.83	2.30	1.04	2.42	0.15	0.63	0.29	0.59	0.25	20.46	100.32	11.94	0	1.00
A_2	2–5	43.10	9.12	23.16	2.37	0.87	2.31	0.15	0.63	0.15	0.49	0.20	17.58	100.13	8.56	0	0.72
A_3	5–11	43.61	10.28	23.82	2.53	0.65	2.25	0.14	0.68	0.19	0.49	0.14	15.54	100.32	5.67	0	0.50
B_1	11–15	44.41	10.94	24.48	2.50	0.75	2.24	0.08	0.72	0.39	0.25	0.09	13.17	100.02	3.71	0	0.32
B_2	15–30	45.10	12.10	24.11	2.71	0.64	2.44	0.12	0.72	0.42	0.26	0.07	11.63	100.32	2.18	0	0.18
B_3	30–36	44.75	12.13	24.27	2.94	0.78	2.55	0.08	0.65	0.46	0.24	0.09	11.36	100.30	2.19	0	0.20
C_1	36+	45.10	12.23	23.87	3.09	1.15	3.56	0.16	1.14	0.13	0.19	0.10	9.45	100.17	1.36	0.18	0.15

Derived data of Miami silt loam colloid

Horizon	Depth (inches)	$\frac{SiO_2}{Fe_2O_3.Al_2O_3}$	$\frac{SiO_2}{Fe_2O_3}$	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{\text{Total bases}^1}$
A_1	0–2	2.57	12.52	3.23	6.68
A_2	2–5	2.52	12.55	3.15	7.17
A_3	5–11	2.43	11.26	3.11	7.24
B_1	11–15	2.37	10.70	3.05	7.30
B_2	15–30	2.40	9.90	3.17	7.04
B_3	30–36	2.37	9.80	3.13	6.48
C_1	36+	2.42	9.93	3.21	6.18

[1] Oxides of magnesium, calcium, potassium, and sodium.

show a trace of bleicherde below the A_0, giving the appearance of a Podzol or Brown Podzolic solum forming at the surface.

The authors have interpeted the tonguing or mingling of eluvial and illuvial horizons in these soils as evidence of destruction of the B horizon. In their experience with the Gray-Brown Podzolic soils, the tonguing is associated with a base saturation which is appreciably less than that in the B horizons which show no evidences of destruction. Where the tonguing is present the base saturation in the horizon of tonguing is usually below 50 per cent, and often below 35 per cent. Kaolin is usually present. If the tonguing is absent, the base saturation is normally above 60 per cent.

The genesis of the Gray-Brown Podzolic soils has been discussed by Cline (1949), Frei and Cline (1949), and McCaleb and Cline (1950) in a series of three papers. In these papers it is pointed out that, in the climatic environment of New York, leaching of bases progresses with time. While carbonates are still present in the solum and the base status is very high, there is intense biologic activity, and little or no evidence of the formation of an illuvial B. At this stage the soil is called a Brown Forest soil. With increased removal of bases, biologic activity decreases somewhat, and the structural aggregates in the B horizon become coated with thick layers of oriented silicate clays indicating a translocation and accumulation of clay. At this stage the soil is considered a Gray-Brown Podzolic soil. With continued removal of bases, the horizon of clay accumulation moves progressively deeper, biologic activity decreases, and there is developed near the surface a horizon of free sesquioxide accumulation in the material which has been the A horizon of the Gray-Brown Podzolic soil. A faint bleicherde develops below the leaf mat. At this stage, the soil is considered a Brown Podzolic soil.

Cann and Whiteside (1955) studied a profile of a soil in Michigan which would be roughly comparable to the final developmental stage studied by Cline and co-workers mentioned above. However, the bleicherde was 1½ inches thick. They assumed that quartz sand had not suffered significant losses, and concluded that the B horizon which showed clay coatings was an illuvial horizon. It would seem, then, that the Gray-Brown Podzolic soils are distinctly different from the soils with a (B) and from the Brown Podzolic soils.

The Gray-Brown Podzolic soils have, in the United States, been called chiefly by that name. They were called Brown Forest soils briefly by Marbut (1927) but there was little use of this name.

In Europe, soils comparable to the Gray-Brown Podzolic soils often have been called simply Braunerde or Brown Forest soils.

In Belgium and the north of France they were called commonly "Terre à briques." Aubert (1938) introduced the name "Sol brun lessivé" for those members of the group that have a mull humus, a thick A_1, an A_2 showing little or no bleaching, and a low ratio of clay accumulation. More strongly leached soils, having usually a moder humus, a more bleached A_2, and a higher clay accumulation ratio, and often having some evidences of destruction of the B horizon, such as bleached silt on the peds and the beginning of formation of bleached tongues from the A to the B, are "Sols lessivés." The most leached members are called "Sols podzoliques."

In Austria they have been designated since 1953 with the general name "Lessivé." In Germany Mückenhausen (1955) introduced the name "Para-Braunerde." In the classification of Stremme (1936) they were called "Brown Forest soils" with a further indication of the degree of bleaching (weakly, moderately, strongly). No good place was provided for these soils in the classification scheme of Laatsch (1937); some of them are included in his "podzolige braune Waldboden," but no doubt others are grouped with the "Brauner Waldboden" of various base status. Also in Kubiena's system (1953) no good place was provided; some of them were included with the "Braunlehm," others with the "Braunerde" and the "Podsolige Braunerde."

In the British Isles they were generally referred to as "Brown Earths" or "Brown Forest soils" of high, medium, or low base status according to their saturation. In 1956 Avery introduced for these soils the name "Leached mull soils" with textural B horizon.

In eastern Europe they have been generally included in the large group of "Brown Earth" or "Brown Forest soils." Further subdivision has often been made on the parent material.

The Gray-Brown Podzolic soils in the United States are largely

confined to relatively recent base-rich unconsolidated or weakly consolidated sediments. Where the land surface can be dated, they are not found on parent materials older than Illinoian unless the present land surface is Illinoian or younger. The parent materials are usually calcareous, but there are many areas of Gray-Brown Podzolic soils developed in slightly acid to alkaline but noncalcareous siltstones, and even sandstones.

These soils are found on the calcareous Wisconsin drifts from New York to Iowa and southern Minnesota. They are widespread on the loess and extend in a belt along the east side of the Mississippi Valley through Mississippi and into Louisiana. In Missouri, Indiana, and Ohio they are common on siltstones and shales, and often occur on sandstones. Scattered areas can be found on the terraces along the Mississippi and its tributaries in the southern states.

The variants with a fragipan are largely restricted to the Mississippi Valley in southern Ohio, Indiana, Illinois, and Missouri, and extending to the south on the loess.

The variants with the A_2 tonguing into the B from above are largely restricted to the northernmost part of the area of occurrence.

If the parent materials are very sandy, the B horizons of these soils are usually a series of "fibers" or lamellae in which clay has accumulated with appreciable amounts of iron.

The distribution according to parent materials in Europe is similar to that in the United States—generally on Pleistocene deposits, drift, and loess wherever they are calcareous or have a basic character. The authors have not seen them in Scandinavia, but have seen them in Scotland, England, the Netherlands, Belgium, France, Germany, Austria, Switzerland, northern Italy, and Yugoslavia, and the literature indicates the probability of their occurrence in Hungary, Poland, and Czechoslovakia. Kellogg (1945) examined soils at Dolgoypudnee Pole near Moscow that were good examples of the Gray-Brown Podzolic soils as classified in southern Michigan and Wisconsin. He considered one of his profiles to be intergrading very slightly toward Planosol and another toward Humic-Gley.

Typically, in Europe the Gray-Brown Podzolic soils have been cultivated for long periods, and the cultivated soils differ in some minor morphologic details from their counterparts in the United States.

Under cultivation, with heavy manuring and frequent clover crops, the earthworms are present in very large numbers and have caused considerable mixing of the horizons. In addition, the A_p horizons have been darkened till they have become as dark as the equivalent Brunizems or Chernozems of the southern Great Plains in the United States. This is illustrated by the two next profile descriptions.

The following profile description was written on the University of Leeds farm in England. It was developed from Wisconsin till, chiefly a mixture of sandstone, shale, and limestone.

Horizon	*Inches*	*Description*
A_p	0–6	Very dark grayish-brown (10YR 3/2, moist) friable loam, weak fine crumb structure, and common worm casts and burrows. Smooth abrupt lower boundary.
A_2	6–10	Dark brown (7.5YR 4/4, moist) loam with weak fine subangular blocky structure, and many worm holes and casts; clear smooth lower boundary.
B_{21}	10–26	Reddish-brown (5YR 4/5, moist) clay loam, firm and plastic; fine to medium subangular blocky structure, with nearly continuous clay skins on ped surfaces; many worm holes and casts.
B_{22}	26–31	Reddish-brown (5YR 4/4, wet) light clay; moderate fine and medium angular blocky structure, with thick continuous clay skins; worm holes continue through this horizon.
C_1	31–48	Yellowish-red (5YR 5/6, moist) calcareous heavy loam or light clay loam. Many partially decomposed limestone fragments.
D	48+	Limestone bedrock.

A similar profile was described in Belgium, formed from loess rather than till, on a light undulating erosion landscape on a 4 per cent slope, as follows:

Horizon	*Inches*	*Description*
A_p	0–10″	Dark brown (10YR 3/3, moist, and 10YR 4/3, crushed) silt loam, friable, nonplastic, with weak, fine-to-medium crumb structure; abrupt smooth lower boundary.
B_{21}	10–22″	A mixture of very dark grayish-brown worm casts and weak medium subangular blocky peds, heavily coated with very dark grayish-brown clay and organic matter (7.5YR 4/4 to 10YR 4/2) but crushing to yellowish-brown (10YR 5/4). Texture is a heavy silt loam, consistence is firm in place, friable when removed, slightly plastic, and slightly sticky; clear smooth lower boundary.
B_{22}	22–25″	Similar to above, but some worm casts are yellowish-brown and calcareous; weak medium-to-coarse subangular blocky structure; some peds and most of the pores are coated with dark brown (7.5YR 4/4); abrupt smooth lower boundary.
C	25″+	Light yellowish-brown (10YR 6/5) silt loam, massive with frequent worm holes, firm in place, friable when removed, calcareous.

The considerable mixing of A and B by earthworms and thick dark coatings of clay and humus below the A_p seem to be the most striking

features of this profile. A study of the degree of mixing has shown that the base color of the A_p is dark brown (10YR 4/3 to 3/3), and the presence of lighter spots is due to the plowing up of parts of the B horizon. One also finds in the A_p pale brown spots (10YR 6/3). These derive from a micro-colluviation that took place on the surface, and have been plowed in. The average volume of fresh parts of the B that have been plowed in is approximately 5 per cent in the profiles studied; the volume of the pale brown lenses from the micro-colluviation scarcely reached 1 per cent. The lower boundary of the A_p is smooth and abrupt, but is crossed by many worm holes and some fine dark humus-coated cracks. In the B_2 the average diameter of the worm holes is 4 to 6 mm.; they are bordered by a clay-humus ring (10YR 3/3 to 10YR 4/3) up to 5 mm. thick. The mass that the worms have reworked thus has an average diameter of about 15 mm. There is an average of 7 to 10 worm holes per 100 $cm.^2$. The average of the material recently reworked is at least 15 per cent. Furthermore, the worm holes, in many places, are enlarged to cavities that are partly filled with coprogenic material comparable to that found on the surface. The borders of the worm holes have a great many fine roots which have finer branches in the pores and cracks and on the surface of the peds. Under pasture and orchard the degree of mixing is generally at least 20 per cent. Careful studies on the mixing of this horizon were carried out by L. Baeyens of the Soil Survey of Belgium; the results will be published in the near future.

The authors have coined the name "anthropic textural B" for the B horizons of the Gray-Brown Podzolic soils that, owing to the influence of management, show this extensive mixing by earthworms and extensive movement of the clay and humus.

A typical noneroded Gray-Brown Podzolic soil was examined during the excursions organized during the first meeting of the Subgroup for Soil Classification and Survey in Europe of F.A.O. in Ghent. The denomination of the profile by the participants was as follows:

Dr. E. Mückenhausen (Germany): Typische Para-Braunerde.

Dr. Ph. Duchaufour (France), Dr. H. Frantz (Austria), Dr. B. Vovk (Yugoslavia): Sol brun lessivé.

Dr. E. Mancini (Italy), Dr. E. Frei (Switzerland): Braunerde.

Dr. P. Stobbe (Canada), Dr. L. Bramao (Portugal): Gray-Brown Podzolic.

Dr. D. Osmond (England): Brown Earth of medium to low base status.

The profiles under forest do not show the earthworm activity described above, but are comparable in general to the Miami silt loam.

In the south of Europe comparable profiles are seen where the climate is continental rather than Mediterranean. The following profile

was seen at the edge of the town of Cerna in Yugoslavia, about 80 miles northwest of Belgrade. The slope was nearly level, and the authors interpreted the parent material to be loess or loess reworked by water. The rainfall here is about 700 mm., with a winter maximum and a secondary spring maximum. The mean annual temperature is about 11° C. The native vegetation was oak forest, but the profile was described in a brickyard. The area had formerly been cultivated.

Horizon	*Inches*	*Description*
A_p	0–9	Dark grayish-brown (10YR 4/2, moist; 5/2.5, dry) silt loam; friable, slightly hard, massive, common worm holes; abrupt lower boundary; some fine iron manganese concretions.
B_1	9–12	Dark grayish-brown (10YR 4/2) silty clay loam, coated very dark grayish-brown (10YR 3/2) weak fine subangular blocky structure; nearly continuous clay skins, but bleached silt shows on surface of clay skins; plastic, sticky; clear smooth lower boundary.
B_{21}	12–25	Dark brown (10YR 3/3 rubbed) heavily silty clay loam or silty clay; moderate medium and coarse prisms breaking to fine angular blocky and subangular blocky peds with thick, very dark grayish-brown (10YR 3/2, moist) continuous clay skins; very hard, plastic, sticky, firm; clear smooth lower boundary.
B_3	25–34	Brown (1Y 4/3) heavy silt loam or light silty clay loam; weak coarse and very coarse prisms with common to nearly continuous clay skins; many very fine pores with frequent clay skins; a few fine distinct mottles of yellowish or strong brown; abrupt irregular lower boundary.
C_{ca}	34–60+	Dark brown (about 1Y 4/3, moist) heavy silt loam; massive, many pores; common medium distinct mottles of strong brown, yellowish brown, and gray; calcareous and fossiliferous, with common lime concretions. Dark clay skins continue in cracks and pores to base of cut.

The B horizon of this profile is similar those of class (*b*) (Section II, 3), the Degraded Brunizems and Reddish Prairie soils. It appears that the soil has been under forest long enough to destroy the dark color of the A horizon, but the dark color of the B horizon persists.

Both in the United States and Europe these soils, under cultivation, often lose the A horizons by erosion, and the plow layer may consist chiefly of the B horizon. Some of the earlier workers misinterpreted such soils, and concluded that they had no illuvial horizon because the finest textures were at the surface. Yet examination of the horizon immediately below the plow layers shows the typical Gray-Brown Podzolic B horizon, with blocky structure and with continuous clay skins coating the peds. No other explanation of some of the literature can be found by the authors.

b. Red-Yellow Podzolic Soils. It was pointed out earlier that the only clear distinction between the yellow members of the Red-Yellow Podzolic group and the Gray-Brown Podzolic group was their geographic relation to the boundary drawn by Marbut (1936). Thus, a number of soils in Virginia, Maryland, Pennsylvania, and New Jersey have been called Gray-Brown Podzolic soils although they are formed from old sediments or even igneous rocks. In recent years more and more of the soil series descriptions have been relating these series to the Red-Yellow Podzolic class.

A profile description and laboratory data on such a soil formed from a granite in Lancaster County, Pennsylvania, taken from the unpublished data of the Soil Survey Laboratory, Beltsville, Maryland, as representative of these soils is given below. The description was written in its present form by J. J. Noll.

Chester silt loam

Horizon	*Inches*	*Description*
A_{00}	—2–1	Mixed hardwood leaves.
A_0	—1–0	Rotted leaves.
A_1	0–3	Black (10YR 2/1) silt loam with weak fine granular structure; very friable; strongly acid; abrupt wavy boundary.
A_2	3–10	Dark brown (7.5YR 4/4) silt loam with weak medium granular, silghtly platy structure; very friable; strongly acid; clear wavy boundary.
B_1	10–12	Strong brown (7.5YR 5/6) heavy silt loam with moderate medium subangular blocky structure; friable; strongly acid; clear wavy boundary.
B_{21}	12–19	Strong brown (7.5YR 5/6) silty clay loam with moderate medium blocky structure; friable; strongly acid; gradual wavy boundary.
B_{22}	19–27	Strong brown (7.5YR 5/6) silty clay loam, moderate medium blocky structure; friable; medium acid; clear broken boundary.
B_3	27–38	Yellowish-red (5YR 5/6) channery silty clay loam; very weak blocky, some platy structure, friable; slightly acid; clear broken boundary; 30 to 40 per cent coarse fragments of schist.
C	38–50	Red to very dark gray (2.5YR 4/6–N3) schistose weathered rock with yellowish-red clay coatings on schist fragments; slightly acid.

Topography: Undulating to gently rolling upland. Slope at sample site is 5 per cent.

Drainage: Surface and internal drainage good. Moderately rapid permeability.

Vegetation: (At sample site) Forest—white oak, red oak, hickory, scarlet oak, chestnut oak, pin oak, dogwood, mountain laurel.

Remarks: This site represents relatively shallow Chester silt loam.

Clay mineral analyses

Horizon	Depth (inches)	Per cent clay ($<2\mu$)	Mineral composition[1] Mi	Vm	Chl	Mt	Kl	Per cent free iron oxides (as Fe_2O_3 < 2 mm. soil fraction)
A_0	1–0							
A_1	0–3	20.0						3.5
A_2	3–10	23.6	x	xx	xx		xx	3.9
B_1	10–12	24.8						4.4
B_{21}	12–19	27.6						5.2
B_{22}	19–27	23.8	x	xx	xx		xx	5.4
B_3	27–38	19.0						5.8
C	38–50+	13.2	x	xx	xx		xx	5.0

Mi = mica; Vm = vermiculite; Chl = chlorite; Mt = montmorillonite; Kl = kaolin.
Relative concentrations: x = detected; xx = moderate.
[1] Determined by X-ray.

Chester silt loam

Horizon	Depth (inches)	Particle size distribution: Very coarse sand 2–1 mm.	Coarse sand 1–0.5 mm.	Medium sand 0.5–0.25 mm.	Fine sand 0.25–0.10 mm.	Very fine sand 0.10–0.05 mm.	USDA silt 0.05–0.002 mm.	Clay <0.002 mm.	Int. silt 0.02–0.002 mm.
A_0	1–0	—	—	—	—	—	—	—	—
A_1	0–3	3.7	4.6	2.8	7.9	6.4[1]	54.6	20.0	39.5
A_2	3–10	3.6	3.3	2.4	6.6	5.6	54.9	23.6	38.8
B_1	10–12	5.7	4.0	2.6	6.5	5.5	50.9	24.8	36.3
B_{21}	12–19	5.1	3.9	2.5	6.3	5.6	49.0	27.6	34.5
B_{22}	19–27	5.9	4.4	2.8	6.7	5.8	50.6	23.8	33.9
B_3	27–38	10.9	8.8	4.2	9.4	8.0	39.7	19.0	28.6
C	38–50+	15.9	13.2	6.0	12.6	11.1	28.0	13.2	18.5

[1] Undecomposed organic matter in sand fraction.

Horizon	Depth (inches)	pH	Organic carbon (%)	Cation exchange capacity (meq./100 g.)	Extractable cations (meq./100 g.) Ca	Mg	H	Na	K	Base sat. (%)
A_0	1–0	—	—	62.3	6.5	4.9	49.7	−0.1	1.2	20
A_1	0–3	4.3	7.3	26.6	0.6	1.1	24.4	−0.1	0.5	8
A_2	3–10	4.5	2.67	13.6	0.1	0.1	13.1	−0.1	0.3	4
B_1	10–12	4.5	0.54	9.2	−0.1	0.1	8.6	0.3	0.2	7
B_{21}	12–19	4.7	0.38	10.1	0.4	0.1	9.3	0.1	0.2	8
B_{22}	19–27	5.0	0.14	9.3	0.1	1.6	7.3	0.2	0.2	22
B_3	27–38	5.1	0.12	5.9	−0.1	0.2	5.3	0.2	0.2	10
C	38–50+	5.0	0.08	6.9	−0.1	−0.1	6.5	0.3	0.1	6

It will be noted that the B horizon is one of clay accumulation, that base saturation is very low, that free iron oxides in the B constitute about 20 per cent of the clay, and that the clays are dominated by kaolin, chlorite, and vermiculite. These are properties common to the Red-Yellow Podzolic soils. The Miami and like soils have a similar textural B, but the clays are dominantly illite and montmorillonite, base saturation in the B is over 60 per cent, and free oxides amount to about 5 to 10 per cent of the clay.

In the United States, the soils of the general character of the profile just described are confined largely to the Coastal Plain and the Piedmont from Virginia to New Jersey, to the valleys of Virginia, Maryland, and Pennsylvania, and to the Allegheny Plateau and the Ozark highlands. Comparable soils south of this area have been called Red-Yellow Podzolic soils.

It was pointed out earlier that Brown and Byers (1938) had suggested that the Chester soils resembled the Red-Yellow Podzolic soils more closely than the Gray-Brown Podzolic soils. Lyford (1952) recognized the occurrence of some Red-Yellow Podzolic soils in the northeastern states mentioned above but considered others to be Gray-Brown Podzolic soils.

In Europe, these soils seem inextensive. They occur in some of the few high rainfall areas bordering the Mediterranean. The authors have seen these soils in Istria and Slovenia, where the name "Podzolized Terra Rossa" was applied to them by Neugebaur and Vovk (1956), though they did not necessarily occur on limestone. Kubiena (1953) has used the term "Bleached Braunlehm" for the more yellow members and "Bleached Rotlehm" for the reddish members. He uses the name "Bleached Terra fusca" or "Bleached Terra rossa" for those occurring on limestone. In western Europe Red and Yellow Podzolic soils occur as scattered relict soils, often buried by the loess mantle, and have sometimes been called Podzolic Brown Earths.

c. Noncalcic Brown Soils. It was pointed out earlier that the Noncalcic Brown soils were not distinguished from the Gray-Brown Podzolic soils except in terms of the climate in which they occur, the Noncalcic Brown soils having a Mediterranean climate with winter rain and summer drought. They were placed in the suborder of "Soils of the forest-grassland transition," together with the Degraded Chernozem by Baldwin *et al.* (1938).

The distinctions that can be made between the Noncalcic Brown soils and the Gray-Brown Podzolic soils are few. Typically, the Noncalcic Brown soils have a somewhat darker surface and have an abrupt transition from the A to the B. The B is an illuvial horizon of clay accumulation and is characterized by prismatic structure. The A hori-

zon of Noncalcic Brown soils is either massive or has very weak crumb structure, and in its micromorphology seems to be quite unlike the A of most Gray-Brown Podzolic soils. The A of the Noncalcic Brown soils is porous and under a hand lens the pores appear to have a smooth glazed lining. The clays seem mobile and concentrated at the contacts between silt or sand particles. Thus, when dry, the A horizon hardens, so that it is extremely difficult to dig with a spade.

Because they occur in areas with pronounced dry seasons, the Noncalcic Brown soils differ from the Gray-Brown Podzolic soils in the seasonal moisture variations. The Noncalcic Brown soils tend to be at or below wilting point in the solum for much longer periods than do the Gray-Brown Podzolic soils.

The B horizon of the Noncalcic Brown soil has uniformly a brownlehm fabric. In the Gray-Brown Podzolic soil, in addition to the brownlehm fabric in the interior of the peds, a Brown Earth fabric also seems to be present in the interior of the peds.

The original concept of the Noncalcic Brown soils assumed that, if a ca horizon[1] were present, the soils could be classified as Brown soils. In recent years soils with ca horizons have been found in California which seem more like the Noncalcic Brown soils than the Brown soils. The name, therefore, is inappropriate for the concept that is currently developing.

In the United States, these soils have been called Noncalcic Brown soils since 1938. This group of soils is believed similar to those called Brown soils by Shaw (1930) and Shantung Brown soils by Thorp (1936). Further study of some of the soils presently called Reddish Prairie and Reddish Chestnut may show that they belong with the group of Noncalcic Brown soils.

Similar soils in Portugal have been called Brown soils of Alentejo by Bramao (1949). In Spain these soils have been called "tierras pardas," "Brown Dry Forest soils," and "Calvero soils" by Del Villar (1937). Kubiena (1953) uses the term "Braunlehm" for the soils that have lost their A horizon, while the A horizon, if present, is designated "Meridional Braunerde."

In Italy Brown Earth seems commonly used. Pallmann uses the name "Insubrian Brown Earth." While in the Mediterranean area these soils are often calcareous, many authors used the name "Calcareous Brown Earth." It seems confusing to state that Calcareous Brown Earth corresponds to Noncalcic Brown soils. In Russia these soils correspond probably to the "Cinnamon soils" of Gerassimov (1956). In a more general way in western Europe one refers to those soils as "Mediterranean Brown soils."

[1] An horizon in which calcium carbonate has accumulated.

A representative profile was described on the middle terrace of the Henares River near Alcala de Henares, about 50 km east of Madrid. The mean annual temperature is about 57° F. and the rainfall is about 16.5 inches, with a pronounced dry summer. Practically all the land is being or has been cultivated. The profile, described in a gravel pit, was as follows:

Horizon	*Inches*	*Description*
A_p	0–9	Dark brown (10YR 3.5/3 moist, 4/3 dry) sandy loam, with some gravel and small stones; massive; hard when dry; abrupt lower boundary.
B_2	9–22	Dark brown (7.5YR 3.5/4 moist, 4/4 dry) light sandy clay or heavy sandy clay loam, with some gravel and small stones; moderate medium prisms, breaking to fine and medium subangular blocks with thick continuous clay skins having a 10YR 3/4 moist color; extremely hard when dry, very plastic and very sticky when wet; clear lower boundary.
C_{ca}	22–35	White (10YR 8/1 moist) and when rubbed light brownish yellow (10YR 6/4 moist) loam or sandy loam; violent effervescence with HCl.
D_{ca}	35–86	Stratified gravel, moderately cemented with lime in layers.
D	86+	Loose gravel, with only weak lime coatings on lower side of gravels.

The ca horizon is common to these soils in this vicinity, but is not universal. On the higher terraces and on the old alluvial fans in this neighborhood, the B horizons have a dark reddish-brown color (5YR 3/4 to 4/4 moist) but are otherwise similar.

In the United States soils of this character are common in the central valley of California, and in parts of western Oregon and southern California. They may also occur in parts of Arizona, New Mexico, and Texas where the soils have been classified as Reddish Prairie and Reddish Chestnut, though further study of these soils is needed.

A common variant of the Noncalcic Brown soils in California and possibly other countries includes an indurated hardpan directly below the B. The hardpan seems to be cemented with both iron and silica.

In Europe, these soils are largely restricted to southern Portugal, Spain south of the Pyrenees, the plains of Italy, Istria, and a narrow belt bordering the Adriatic on the east. They also seem to occur in Greece and along the borders of the Black Sea. Many authors believe that relicts of fossil Noncalcic Brown soils occur in central and western Europe. With our present limited knowledge of these soils, this is certainly difficult to prove. In the Mediterranean area these soils often occur in close association with Red and Yellow soils and one finds all

kinds of intergrades. Very often the younger parts of the landscape (low terraces or lower planation levels) have brown soils, whereas older landscape forms (high terraces, for example) have red soils.

III. Summary and Conclusions

This study of Braunerde has been limited to Europe and the United States. Many other soils called Brown Forest or Braunerde, such as the Ando soils of the Pacific area, the Brown soils of northern Africa, the tropical Brown Earths, and the Brown Earths of high alpine areas have not been discussed.

Generally, within the last few years, there has been a close correspondence between the soil classifications in the United States and in western Europe, but the correspondence has not always been reflected in the names used.

The soils with a (B) can be subdivided into two varieties. The Sol Brun Acide, which can be considered a climatic or zonal soil, is characterized by a (B) with slight formation of silicate clays, and with segregation but no appreciable eluviation and illuviation of oxides or clays. It is formed mostly on moderately acidic parent materials, and comes climatically next to the Podzols and Brown Podzolic soils.

The kind of soil currently known as Sol Brun Acide has generally been called Braunerde or Brown Forest soil in Europe, whereas in the United States it was first called Gray-Brown Podzolic soil and then Brown Podzolic soil.

The base-rich Brown Forest soils having a (B) seem to be intrazonal soils, with intense horizon mixing due to high biologic activity. With continued leaching, these soils seem to develop into Gray-Brown Podzolic soils or Sols Bruns Lessivés.

The name Brown Forest soil has been used in the United States for intrazonal calcimorphic soils, developed on basic and usually calcareous parent materials, still in a stage of essentially complete saturation by bases. They are formed under decidious forest in temperate regions. They have surface horizons of very dark brown, relatively rich in humus (mull) grading through lighter colored soil into the parent material with no appreciable illuvial horizon.

In contrast, in the Scandinavian countries the same name, "Brown Forest Soil," has been used for soils having illuvial horizons of sesquioxides but lacking a bleached A_2 horizon. Such soils were at one time called Gray-Brown Podzolic soils in the United States, and later renamed Brown Podzolic. Such soils were called unbleached Rusty-colored Forest soils by Stremme and his school.

The authors believe the soils called Brown Podzolic belong morphologically and genetically with the Podzol group. The absence of a

bleached A_2 horizon may be explained by mixing of horizons by biologic or other means.

The name Gray-Brown Podzolic soil has been chiefly used in the United States for soils having an illuvial horizon of silicate clay minerals, although at one time the Brown Podzolic soils and Sol Brun Acide were included. The same soils were principally called "Brown Forest" in Stremme's terminology, Brown Earth in the British Isles, and Sol (brun) lessivé in France.

The Gray-Brown Podzolic soils seem to develop on parent materials with an appreciable content of bivalent bases. The silicate clay illuvial horizon characteristic of these soils is probably due in most cases to flocculation of the clay by the bivalent cations. With continued leaching one often finds destruction of the B horizon, and a Brown Podzolic soil or a Podzol tends to develop in the A_2 horizon of the Gray-Brown Podzolic soil. Climatically these soils are found in somewhat warmer and drier climates than the Podzol and the Sol Brun Acide, or are restricted to young calcareous parent materials. In general, these soils are restricted to relatively recent land surfaces.

The Mediterrean Brown Earths or Noncalcic Brown soils are morphologically very similar to the Gray-Brown Podzolic soils, but probably have a somewhat different genesis. A possible genetic difference is indicated by the fact that the Noncalcic Brown soils become redder with age, as do the Gray-Brown Podzolic soils, but to the best of the author's knowledge never show evidences of destruction of the textural B horizon. The Noncalcic Brown soils also often have an indurated pan, cemented at least in part by silica or silicates, indicating a greater mobility of the silica. The Noncalcic Brown soils occur in climates with dry and hot summers.

The Red-Yellow Podzolic soils have members similar in visible morphology to the Gray-Brown Podzolic soils. However, the flocculation of the clay cannot be due to bivalent cations, as these may be present only in traces. Rather, one suspects that the clay is flocculated by iron. Evidences of destruction of the B horizons are very weak or absent in these soils.

The names "Braunerde" or "Brown Forest soils" have, during the past fifty years, been defined and used quite differently by various authors. Because the same names have been used for unlike soils the literature is confusing, and the results of experience reported have been misinterpreted. For example, one of the current textbooks used in many universities defines the Brown Forest soil as a calcimorphic soil, with a surface which is nearly neutral but is the most acid horizon, implying a calcareous subsoil. This definition fits the concept of Cline (1949). These authors in a later section cite the European literature with the

implication since they use the name Brown Forest soil that, under Norway spruce stands, a bleicherde develops in the calcimorphic soils within a few decades. They also point out that the white pine has been reported to have the same effect on the Brown Podzolic soils in New England. The reader might wonder why a bleicherde develops within a few decades under Norway spruce in Europe in a soil which has a nearly neutral surface and a calcareous subsoil. Within the authors' experience bleicherde does not develop in this kind of soil, but does develop rather quickly in the Brown Podzolic soil, a kind of soil included with the Brown Forest soil or Braunerde in Europe. The experience on the two continents then is the same, but one would not understand this from the literature.

The confusion in names results from at least two causes. First, most of the currently recognized great soil groups were named and defined before the development of a vocabulary of defined terms for describing soils. One man's red might be the same as another man's brown, but the great emphasis was placed on color. Second, with the increased knowledge of soils we have been able to write more and more precise definitions of great soil groups, including properties which were unknown to Ramann. This is a natural consequence of our increased knowledge, but soil scientists have in general retained the same names under the more precise definitions, and there has not always been general agreement on the new definitions. The current American concept of the Brown Forest soil is very narrow and is different from the European. Usage is not the same in all European countries, but in general the concept of Brown Forest soil or Braunerde is much broader than the American and includes the American concept.

In the authors' opinion, it was a mistake when the name Brown Forest soil was reintroduced in the United States with its very restricted definition. A new name would have prevented at least some of the confusion. Then too, authors using a term which has been redefined do not always clarify the sense in which they use the term by citing the definition they follow.

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